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Review of Radioisotopes as Radiological Weapons

Carl A. Curling
Alex Lodge

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INSTITUTE FOR DEFENSE ANALYSES
4850 Mark Center Drive
Alexandria, Virginia 22311-1882

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Executive Summary

A simple methodology for evaluating the credibility of radiological material as a threat was developed. This methodology compares the largest quantity of radioactive material typically found in a single instrument or device that is available in commercial practice ("P") with the quantity of radioactive material necessary for it to pose a sufficient threat to be of concern ("C"). If the ratio of "P" to "C" is high (0.1 or greater), it is more credible that the radioactive material could be used in a radiological weapon. A P/C ratio of 0.1 means that 10 sources of that isotope, available in commercial practice, would be required to pose the threat of concern. A P/C ratio of more than 0.1, means *less* than 10 sources would be needed, and a P/C ratio of less than 0.1 but greater than 0.001 means more than 10 but less than 1,000 sources would be needed. Procuring up to 1,000 sources in commercial practice is regarded as unlikely. The P/C ratio is constructed so that the higher the P/C ratio, the more credible it is that a suitable source can be found to pose the threat of concern. This method of comparison does not imply that a radioactive material with a low P/C ratio should not be of concern, but the P/C ratio allows for a prioritization of radiological materials as threats.

Each of the multitude of possible radiological material dispersion mechanisms for a radiation dispersal device (RDD) is tailored to produce a different impact. Malicious actors can employ RDDs to deny area access, cause psychological casualties, and/or cause acute radiation injury. Before a credible plan that estimates the impact from the use of a radiological weapon can be attempted, the definition of credible radiological weapon is necessary. Simply stated, a credible radiological weapon must be physically possible and, if used, must result in a significant impact.

This analysis is applicable to any scenario of interest for a radiological weapon event but is applied in this analysis to a limited set of scenarios that generally have the same criterion: acute radiation dose of 1.25 sieverts (Sv), which is sufficient to cause radiation injury symptoms in most of the population in a short period of time. This methodology could be also applied to other scenarios (if that is the desire of the analyst or planner) as long as the effect of concern (contamination, exposure, or dose level) can be defined with respect to the activity present in the radiological weapon.

A list of common devices containing radioactive materials is published by the IAEA in TECDOC-1344.[1] This list includes how they are used ("Practice") and some of their physical properties that are significant with respect to their use as a radiological weapon. The practices included in this analysis are those representative of the highest typical activity of that radioisotope, the amount of radioactive material found with that practice (Activity of Practice, "P").

The different types of radiological weapons are categorized by dispersal mechanism or route of exposure and can be evaluated based upon impacts of concern, radioisotopes of concern, availability of sources, and a hypothetical event. Five dispersal mechanisms,[2] which encompassed seven different types of exposure, were evaluated. Each scenario allowed the definition of the impact of concern, which, in turn, allowed the calculation of the quantity of each radioisotope that would result in that impact (Activity of Concern, "C"). Using a selection criterion based upon dispersal mechanisms, radiological parameters, the quantities of radioisotope required, commercial availability of sources, security of the sources, and the physical states of the material, a list of radioisotopes of greatest concern was evaluated for each method of dispersal. Each of the evaluations results in an assessment of the credibility of that radiological weapon as a threat. The following table indicates which isotopes in each scenario are unlikely but credible radiological threats ($0.001 < P/C < 0.1$), are credible radiological threats ($P/C > 0.1$), and are of the appropriate physical state to be used in that scenario.

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[1] International Atomic Energy Agency, *Categorization of Radioactive Sources*, IAEA-TECDOC-1344 (Vienna, Austria: Radiation Safety Section, 2003), http://www-pub.iaea.org/MTCD/publications/pdf/te_1344_web.pdf.

[2] An RED, an explosive RDD, an aerosol RDD, an ingestion RDD, and an immersion RDD.

Credibility of Radiological Threat

Isotope	Symbol	RED (TBq/1.25 Sv at 1 m in 1 Hr.)	Explosive RDD		Aerosol RDD: Submersion in Contaminated Air		Aerosol RDD: Inhalation of Contaminated Air		Aerosol RDD: Deposition on Skin	Ingestion of Contaminated Water (1.25 Sv from Drinking 10 L from 40 m³)
			Acute Health Effects (1.25 Sv/hr. over 10,000 m²)	Aerial Denial Effects (0.02 mSv/hr. over 10,000 m²)	Whole Body (1.25 Sv/hr. over 30,000 m³)	Skin (1.25 Sv/hr. over 30,000 m³)	Whole Body (1.25 Gy from 0.9 m3 over 30,000 m³)	Respiratory Tract (1.25 Gy from 0.9 m3 over 30,000 m³)	Skin Contamination (1.25 Sv/hr. over 9,100 m²)	
Hydrogen-3 (Tritium)	^{3}H	o	N/A	N/A	o	N/A	o	o	N/A	●
Phosphorus-32	^{32}P	o	o	●	o	o	●	●	o	✓
Iron-55	^{55}Fe	N/A	N/A	N/A	N/A	N/A	o	o	o	o
Cobalt-57	^{57}Co	o	o	●	o	o	o	o	o	o
Cobalt-60	^{60}Co	✓	✓	✓	✓	✓	✓	✓	✓	✓
Nickel-63	^{63}Ni	o	N/A	N/A	N/A	N/A	o	o	N/A	o
Germanium-68	^{68}Ge	o	o	o	o	o	o	o	o	o
Selenium-75	^{75}Se	●	o	✓	●	●	✓	●	▯	✓
Krypton-85	^{85}Kr	o	o	●	o	o	N/A	N/A	N/A	N/A
Strontium-90	^{90}Sr	✓	o	✓	o	✓	✓	✓	✓	✓
Molybdenum-99	^{99}Mo	o	o	✓	o	o	o	●	o	●
Palladium-103	^{103}Pd	o	o	o	o	o	o	o	o	o
Ruthenium-106/Rhodium	^{106}Ru/Rh	o	o	o	o	o	o	o	o	o
Cadmium-109	^{109}Cd	o	o	o	o	o	o	o	o	o
Iodine-125	^{125}I	o	o	✓	o	o	o	o	o	o
Iodine-131	^{131}I	o	o	✓	o	o	o	o	o	o
Caesium-137	^{137}Cs	✓	●	✓	●	✓	✓	✓	✓	✓
Promethium-147	^{147}Pm	o	o	o	o	o	o	o	o	o
Gadolinium-153	^{153}Gd	o	o	✓	o	o	o	●	o	o
Ytterbium-169	^{169}Yb	●	o	✓	o	o	o	✓	o	●
Thulium-170	^{170}Tm	o	o	✓	o	●	✓	✓	✓	●
Iridium-192	^{192}Ir	✓	o	✓	●	●	✓	✓	✓	✓

Credibility of Radiological Threat (Continued)

		RED (TBq/1.25 Sv at 1 m in 1 Hr)	Explosive RDD		Aerosol RDD: Submersion in Contaminated Air		Aerosol RDD: Inhalation of Contaminated Air		Aerosol RDD: Deposition on Skin	Ingestion of Contaminated Water (1.25 Sv from Drinking 10 L from 40 m³)
Isotope	Symbol		Acute Health Effects (1.25 Sv/hr over 10,000 m²)	Aerial Denial Effects (0.02 mSv/hr over 10,000 m²)	Whole Body (1.25 Sv/hr over 30,000 m³)	Skin (1.25 Sv/hr over 30,000 m³)	Whole Body (1.25 Gy from 0.9 m3 over 30,000 m³)	Respiratory Tract (1.25 Gy from 0.9 m3 over 30,000 m³)	Skin Contamination (1.25 Sv/hr over 9,100 m²)	
Gold-198	^{198}Au	o	o	✓	o	o	o	o	o	o
Polonium-210	^{210}Po	o	o	o	o	o	●	✓	o	●
Radium-226	^{226}Ra	o	o	o	o	o	o	✓	o	o
Plutonium-238	^{238}Pu	o	o	✓	o	o	✓	✓	o	✓
Plutonium-239/Beryllium	$^{239}Pu/Be$	o	o	o	o	o	✓	✓	o	●
Americium-241	^{241}Am	o	o	✓	o	o	✓	✓	o	●
Americium-241/Beryllium	$^{241}Am/Be$	●	o	✓	o	o	✓	✓	o	✓
Curium-244	^{244}Cm	o	o	o	o	o	●	✓	o	o
Californium-252	^{252}Cf	o	o	o	o	o	●	✓	o	o

Legend:

o P/C Ratio < 0.001.
● 0.001 < P/C Ratio < 0.1.
✓ P/C Ratio > 0.1.
✓ P/C Ratio > 0.1 and appropriate physical form.

Radiological Threats

Radiation Exposure Device (RED)

- The simplest radiological threat would be the placement of unshielded radioactive material in a heavily trafficked area as an RED, with the placement of a compact source with exposure to the whole body.
  - *Primary impact of concern.* Acute health effects from whole-body exposure, dose rate > 1.25 Sv/hr. at 1 m.
  - The low technological expertise required, significant pool of viable radioisotopes, and practical number of sources containing those radioisotopes makes RED construction and deployment a possibility. In addition, these sources may not be as well secured as others and might be obtained with medium effort. Combined with the likelihood of causing acute radiation injury amongst a limited population and sowing panic an RED poses a credible threat against this scenario.

Explosive Radiation Dispersal Device (RDD)

- This scenario postulates the uniform dispersal of radioactive material over an area of 10,000 m^2 (a radius of about 56.5 m), selected as representative of an area of concern for contamination.
  - *Primary impact of concern.* Acute health effects from whole-body exposure, dose rate > 1.25 Sv/hr.
  - *Alternate impact of concern.* Area denial due to external dose rate > 0.02 mSv/hr.
  - Very few of the isotopes considered would be expected to contaminate a large area at a level acutely hazardous to health when used in an explosive RDD. Five isotopes—^{90}Sr, ^{137}Cs, ^{238}Pu, ^{241}Am, and ^{241}Am/Be—are credible candidates to be used in an explosive RDD to produce area denial effects.

Aerosol RDD

- **Aerosol RDD/submersion in a cloud of contaminated air.** This scenario postulates the uniform dispersal of radioactive material inside a building with a volume of 30,000 m^3, approximately the volume of a (rather modest) five-story building.
  - *Primary impact of concern.* Acute health effects from external whole-body exposure, dose rate > 1.25 Sv/hr.

- – *Alternate impact of concern.* Acute health effects from cutaneous exposure, dose rate > 1.25 Sv/hr.
- – Only ^{90}Sr and ^{137}Cs are credible candidates to be used in an aerosol RDD and only to produce a significant effective dose equivalent rate to the skin from submersion in a (semi-infinite cloud) of contaminated air.

- **Aerosol RDD/inhalation of contaminated air.** This scenario postulates the uniform dispersal of radioactive material inside a building with a volume of 30,000 m^3.
  - – *Primary impact of concern.* Acute health effects from dose to the whole body from inhalation of contaminated air, committed "Relative Biological Effectiveness (RBE)"-weighted dose > 1.25 Sv.
  - – *Alternate impact of concern.* Acute health effects from dose to the respiratory tract from inhalation of contaminated air, committed RBE-weighted dose > 1.25 Sv.
  - – Six isotopes—^{90}Sr, ^{137}Cs (respiratory tract only), ^{238}Pu, ^{241}Am (respiratory tract only), ^{241}Am/Be, and ^{252}Cf (respiratory tract only)—are credible candidates to be used in an aerosol RDD to produce a significant committed RBE-weighted dose to the whole body or respiratory tract from inhalation of contaminated air.
- **Aerosol RDD/skin contamination from deposition of contamination from the air.** This scenario postulates the uniform dispersal of radioactive material inside a building with a surface area of 9,100 m^2.
  - – *Primary impact of concern.* Acute health effects from contact exposure of the derma of the skin, dose rate > 1.25 Sv/hr.
  - – Two isotopes—^{90}Sr and ^{137}Cs—are credible candidates to be used in an aerosol RDD to produce a significant committed RBE-weighted dose rate when considering skin contamination effects. The technological requirements, coupled with low impacts, diminish the credibility of an attack consisting of an aerosolized dispersal of radioactive material. Therefore, an aerosol RDD is not a credible threat for producing acute radiation injury in this scenario.

Ingestion RDD

- This scenario postulates the uniform dispersal of radioactive material inside a volume of 40 m^3, approximately the volume of a large tanker truck, with ingestion of 2 L of contaminated water per day for a period of 5 days, for a total of 10 L.

– *Primary impact of concern.* Acute health effects from committed RBE-weighted dose to the whole body (red bone marrow) from ingestion, dose > 1.25 Sv.

– Just one isotope—^{137}Cs—is a credible candidate to be used in an ingestion RDD to produce a significant committed RBE-weighted dose to the whole body from ingestion of contaminated water. Despite the high impacts of ingested radioactive sources, the obstacles against the ingestion delivery vector are such that ingestion based RDDs do not qualify as a credible threat against most of the populace.

Immersion RDD

- Immersion in gaseous radioactive material is the most difficult of the scenarios considered in this paper. Only a limited number of radioactive materials are gasses at room temperature and pressure, such as Tritium or various isotopes of argon, krypton, or xenon. It would require a high quantity of radioactive material in a relatively small enclosed space to result in significant dose to the whole body (red marrow). Immersion in radioactive material is not considered a credible threat.

This analysis leads to the conclusion that radiological weapons should be considered as credible threats to U.S. military operations. In evaluating a number of different RDD scenarios, ^{60}Co, ^{75}Se, ^{90}Sr, ^{137}Cs, ^{170}Tm, ^{192}Ir, ^{238}Pu, ^{239}Pu/Be, ^{241}Am, ^{241}Am/Be, ^{244}Cm, and ^{252}Cf were evaluated as credible candidates to be used in some form—often several forms—of radiological weapon threat. Although technological challenges are involved, radioactive material is available commercially in amounts that provide a credible capability to pose a threat as a radiological weapon.

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1. Introduction

A. Overview

In 2013, the U.S. Army Office of the Surgeon General (OTSG) tasked the Institute for Defense Analyses (IDA) to "identify and illustrate the applicability of using current casualty estimation methodologies to develop planning parameters for tactical and terroristic threats of the use of radiation exposure devices (RED) [pronounced R-E-D)], radiation dispersal devices (RDD), and improvised nuclear devices (IND), as well as conventional nuclear weapons."[1] To accomplish this task, there must be a clear understanding of the threat that these weapons pose, the kinds of hazards that these weapons present, and the kind of casualties that would result. In the process of the analysis for the original task, a simple methodology for evaluating the credibility of a radiological material as a threat was developed. This methodology compares the quantity of radioactive material present in commercial practice ("P") with the quantity of radioactive material necessary for it to pose a sufficient threat to be of concern ("C"). If the ratio of "P" to "C" is high (0.1 or greater), it is more credible that the radioactive material could be used in a radiological weapon. This method of comparison does not imply that a radioactive material with a low P/C ratio should not be of concern, but the P/C ratio allows for a prioritization of radiological materials as threats.

B. Assumptions

This analysis is applicable to any scenario of interest for a radiological weapon event but is applied in this analysis to a limited set of scenarios that generally have the same criterion: acute radiation exposure of 1.25 gray (Gy), which is sufficient to cause radiation injury symptoms in most of the population in a short period of time. This methodology could be applied to other scenarios (if that is the desire of the analyst) as long as some endpoint of concern can be defined with respect to the activity present in the radiological weapon. Other assumptions used in this analysis include the following:

- The calculation of dose equivalent assumes a simplified structure of the quality factors (QFs) applied to the absorbed dose. Since the radiation QFs for gamma and beta radiations are both unity (1), whole-body and cutaneous radiation dose will be expressed as absorbed dose in units of Gy instead of dose equivalent

[1] Institute for Defense Analyses, "CBRN Casualty Estimation and Support to the Medical CBRN Defense Planning & Response Project," Project Order CA-6-3079 Amendment No. 5 (Alexandria, VA: Institute for Defense Analyses 14 November 2013), 4.

with units of sievert (Sv) without altering the numerical values.[2] Within the International Atomic Energy Agency (IAEA), committed “Relative Biological Effectiveness (RBE)”-weighted dose, ADT(Δ), in units of gray-equivalent (Gy-Eq), was used for evaluating the risk of developing severe deterministic health effects (acute radiation injury) after the intake of a radioisotope. The committed RBE-weighted dose ADT(Δ) in the organ or tissue T is defined as the time integral of the RBE-weighted dose rate in the organ or tissue over time Δ after an intake of a radioisotope of concern.[3] For this paper, the committed RBE-weighted dose (Gy-Eq) is assumed to be equal to the dose equivalent (Sv).

- For area denial, the U.S. Nuclear Regulatory Commission (NRC) standard for restriction of access is as follows: the dose in any unrestricted area from external sources does not exceed 0.02 millisievert (mSv) in any 1 hr.[4] While this is a civilian standard for exposure to radioactive materials regulated by the NRC, it will be assumed to also be useful as a limit for restriction of access in military scenarios.

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[2] North Atlantic Treaty Organization (NATO), *AMedP-8(C): NATO Planning Guide for the Estimation of CBRN Casualties*, STANAG 2553 (Brussels, Belgium: March 2011).

[3] International Atomic Energy Agency, *Dangerous Quantities of Radioactive Materials (D-Values)*, Emergency Preparedness and Response EPR-D-VALUES 2006 (Vienna, Austria: Radiation and Transport Safety Section, August 2006), 25, 133, http://www-pub.iaea.org/MTCD/publications/PDF/EPR_D_web.pdf.

[4] United States Nuclear Regulatory Commission, “Subpart D--Radiation Dose Limits for Individual Members of the Public,” May 21, 1991, last updated December 2, 2015, http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/part020-1301.html.

2. Radiological Weapons

In 2002, Dr. Henry Kelly testified before the U.S. Senate Committee on Foreign Relations and made the bold assertion that "the threat of [a] malicious radiological attack in the US is quite real, quite serious, and deserves a vigorous response."[5] Dr. Kelly's comments spurred a media frenzy over the possibility of radiological attacks, with most of the focus on dirty bombs. The issue was still of concern in 2014, with Senator Thomas Carper of Delaware leading the charge for the security of radiological sources that could potentially be used in a dirty bomb. His opening statement before the Senate Committee on Homeland Security and Governmental Affairs contained the following remarks: "A dirty bomb is any kind of crude explosive device that, when detonated, disperses radiation around and beyond the blast. If a dirty bomb successfully goes off, those who survive the blast can be exposed to harmful amounts of radiation that could cause sickness or even death. Moreover, a dirty bomb could render areas uninhabitable for many years, making it a highly disruptive weapon."[6] While the focus of Dr. Kelly and Senator Carper are on explosive means of dispersal, radiological materials can be used maliciously in several ways.

To estimate how many casualties could result from the use of a radiological weapon, the definition of credible radiological weapon is necessary. A basic review of the concepts of radiation and radioactive decay is available in Appendix A, if needed. Simply stated, a credible radiological weapon must be physically possible and must result in a significant impact.

A. Dispersal Mechanisms

A multitude of radiological material dispersion mechanisms are possible. In order of increasing technical difficulty, the primary mechanisms are as follows: (1) an RED (easiest), (2) an explosive RDD, (3) an aerosol RDD, (4) an ingestion RDD, and (5) an

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5 *Dirty Bombs and Basement Nukes: The Terrorist Nuclear Threat: Hearing Before the U.S. Senate Comm. on Foreign Relations*, 107th Cong. (March 6, 2002) (statement of Dr. Henry Kelly, President, Federation of Scientists), https://babel.hathitrust.org/cgi/pt?id=uc1.b5155060;view=1up;seq=46.

6 *Securing Radiological Materials: Examining the Threat Next Door: Hearing Before the U.S. Senate Comm. On Homeland Security & Governmental Affairs*, 113th Cong. (June 12, 2014) (statement of Chairman Thomas R. Carper D (DE)), http://www.hsgac.senate.gov/hearings/securing-radiological-materials-examining-the-threat-next-door.

immersion RDD (in a cloud of radioactive gas) (most difficult). An RDD is "the combination of radioactive material and the means (whether active or passive) to disperse that material with malicious intent, without a nuclear detonation, that could (1) impact national security, national economy, national public health and safety, or any combination thereof or (2) require a robust, coordinated Federal response to save lives, minimize damage, and/or provide the basis for long-term community and economic recovery (which includes the cost for decontamination and environmental cleanup efforts)."[7] It is important to note that this definition of an RDD is not synonymous with the layman's term "dirty bomb," which is sometimes incorrectly used interchangeably when speaking on the subject. A dirty bomb is a subset of RDDs classified as an explosive RDD. An alternative malicious use of radioactive materials is through an RED, which is "an object used to maliciously expose people, equipment, and/or the environment to ionizing radiation, without dispersal of the radioactive material, that could cause debilitating injury to people exposed for a period of minutes to hours, or could be fatal to people exposed for a period of minutes to days."[8] A typical example of an RED is an unshielded point source placed in a high traffic area. Radiological weapons harness the effects of harmful ionizing radiation to cause impacts.

B. RDD Impacts

Each RDD method of dispersal is tailored to produce a different impact. The main proposed use of radiological weapons is to induce fear in a population. These weapons are sometimes termed "weapons of mass disruption" due to the relatively low number of casualties in contrast to the disproportionate fear surrounding a radiological attack. The fear is based upon the invisible nature of radiation and plays upon public ignorance of its effects. Malicious actors can harness this fear by employing RDDs to deny area access, cause psychological casualties, and/or cause acute radiation injury.

Area denial is a unique aspect of radiological dispersal devices. While possible to achieve through other means (e.g., as cluster munitions or chemical agents), an area contaminated with radioactive material can be denied for a significant time period. Radioactive particles can bind to porous materials, disperse along air currents, and settle on the ground. An area contaminated with radiological particles may require extensive decontamination. Current decontamination practices include sandblasting contaminated surfaces, dust filtering, painting over structures, removing contaminated topsoil, and several iterations combined with testing. Contaminated structures may need to be demolished, and access to the

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7 Radiation Source Protection and Security Task Force, *The 2010 Radiation Source Protection and Security Task Force Report* (Washington, DC: United States Nuclear Regulatory Commission, August 11, 2010), 7–8, http://www.nrc.gov/security/byproduct/2010-task-force-report.pdf.

8 Ibid., 8.

area may be affected for long periods of time. Contaminated areas may never recover, even after the costly process of decontamination, due to public fear. This situation was observed in the area surrounding Chernobyl, which is currently deemed habitable by government standards, yet is still avoided because of an unfounded public concern of contamination. Area denial is of highest concern in an urban environment.

Acceptable limits for radiation contamination vary widely between agencies, with the commonly accepted "as low as reasonably achievable" (ALARA) approach to exposure serving as a common ground. However, decontaminating an area to a level in which no radiation is present is impossible. Therefore, this document will refer to the NRC standard of 0.02 mSv per hour[9] as the standard above which an area would be regarded as radioactively contaminated and require decontamination before it is suitable to be reoccupied.

For RDD attacks (compared to conventional explosives), a disproportionate number of psychological casualties are expected. Radiological attacks cause mass panic in a population because radiation is invisible and there is a distinct lack of education on the topic. Driven by fear of possible exposure, many people—probably many more than those who are actually affected—will present themselves for medical care. These "worried well" will oversaturate medical facilities and prevent those who need care from getting it. First responders, too, can experience profound psychological effects from participating in the response to an incident and will need assistance.[10] There is currently no algorithm for predicting the number of psychological casualties that would result from a traumatic event, but estimates for a radiological attack are high. An IAEA report on a real-world event claimed that, "the accident in Goiânia had a great psychological impact on the Brazilian population owing to its association with the accident at the Chernobyl nuclear power station in the USSR [Union of Soviet Socialist Republics] in 1986. Many people feared contamination, irradiation, and damage to health; worse still, they feared incurable and fatal diseases."[11] Goiânia is considered the worst case of incidental exposure to date and gives valuable insight into the probable effects of the malicious dispersal of radiological materials.

Deterministic impacts are those impacts that are immediately caused by exposure to ionizing radiation that penetrates internal organs. As the dose increases, the corresponding impact on health increase in severity. A victim of an RDD will either be contaminated,

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[9] United States Nuclear Regulatory Commission, "Subpart D--Radiation Dose Limits for Individual Members of the Public."

[10] U.S. Department of Health and Human Services, "Radiological Dispersal Device Playbook: Introduction," last updated July 2, 2015, http://www.phe.gov/Preparedness/planning/playbooks/rdd/Pages/intro.aspx.

[11] International Atomic Energy Agency, *The Radiological Accident in Goiânia*, STI/PUB/815 (Vienna, Austria: IAEA, 1988), 115, http://www-pub.iaea.org/mtcd/ publications/pdf/pub815_web.pdf.

exposed, or both. Radioactive contamination results from ingestion, inhalation, or cutaneous exposure to radioisotopes.[12] A contaminated person is radioactive and must be decontaminated to prevent further harm to himself/herself or others. In addition, an internally contaminated individual will be subject to continuous exposure from an ingested or inhaled radioisotope. A person can also be irradiated but not contaminated when placed in the vicinity of an unshielded source. REDs or RDDs with gamma- or neutron-emitting radioisotopes are the highest risk for external exposure. A person irradiated by an external source is not contaminated and will not require decontamination.

[12] U.S. Department of Health and Human Services, "Radiation Emergency Medical Management (REMM),"last updated January 12, 2016, http://www.remm.nlm.gov/contamimage_top1.htm.

3. The Radiological Threat

A. Radiological Weapon Selection Process: Which Materials Pose a Threat?

"At the most fundamental level, radiological sources are used for three purposes: (1) to kill or otherwise alter organisms or tissue, (2) to generate energy on a localized and/or remote basis, or (3) to scan objects or provide other types of measurements."[13] Common industrial devices that use radioisotopes include thickness and density gauges, food irradiators, radiographic cameras, well logging devices, brachytherapy devices, medical tracers, and radioisotope thermoelectric generators (RTGs). This list is by no means complete; rather, it gives a general idea of the wide variety of sources that use radioisotopes.

Each radioactive source contains differing amounts, forms, and protective shielding of radioisotopes. To aid nations in differentiating radioactive sources, the IAEA published TECDOC-1344.[14] This document provides an internationally standardized, five-category system to classify dangerous radioactive sources. The IAEA defines a dangerous source as "a source that could, if not under control, give rise to exposure sufficient to cause severe deterministic effects."[15] The categories are based upon the magnitude of exposure and time required to cause deterministic effects. Categorization is then used to prioritize the threat and the required security for specific types of radioactive sources. A list of common devices and their associated categories is provided IAEA TECDOC-1344, with proposed guidance for security of Category 1–3 sources annotated in the IAEA *Code of Conduct on the Safety and Security of Radioactive Sources*.[16]

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[13] Gregory J. Van Tuyle et al., *Reducing RDD Concerns Related to Large Radiological Source Application*, LA-UR-03-6664 (Los Alamos, NM: Los Alamos National Laboratory (LANL), September 2003), 16, https://www.hsdl.org/?view&did=441986.

[14] International Atomic Energy Agency, *Categorization of Radioactive Sources*, IAEA-TECDOC-1344 (Vienna, Austria: Radiation Safety Section, 2003), http://www-pub.iaea.org/MTCD/publications/pdf/te_1344_web.pdf.

[15] Ibid., 11.

[16] International Atomic Energy Agency, *Code of Conduct on the Safety and Security of Radioactive Sources*, IAEA/CODEOC/2004 (Vienna, Austria, Division of Radiation and Waste Safety, January 2004), 15–16, http://www-pub.iaea.org/MTCD/publications/PDF/code-2004_web.pdf.

A list of radioisotopes that could be considered as possible sources for radiological weapons can be derived from various source listings of industrially applied radioisotopes. For this analysis, the list of isotopes was derived from the IAEA[17] and is provided in Table 1. From the U.S. regulatory perspective, the list of radioisotopes of concern is published by the NRC.[18] The list of radioisotopes in Table 1 is all of the radioisotopes in TECDOC-1344, which includes the NRC radioisotopes of concern, how they are used ("Practice"), and some of their physical properties that are significant with respect to their use as a radiological weapon. The practices listed are those representative of the highest typical activity of that radioisotope. Table 2 also lists the radioisotopes and includes the amount of radioactive material found with that practice (Quantity (activity) of Practice, "P"), associated D-values, and IAEA categories. (The D-values are excerpted from *Dangerous Quantities of Radioactive Materials (D-Values)*.[19]) Figure 1 is an illustration of the relative "typical" activities of the largest (most radioactive) practices for each radioisotope. A complete list of the different practices associated with each isotope and the range of activities for those practices can be found in Appendix B.

Table 1. Isotopes Considered as Potential Radiological Weapons

Isotope	Symbol	Practice	Half-Life	Radiation Type	Primary Form
Hydrogen-3 (Tritium)	^{3}H	Tritium targets	12.32 y	Β	Liquid
Phosphorus-32	^{32}P	Medical (unsealed)	14.3 d	Β	Powder
Iron-55	^{55}Fe	X ray fluorescence analyzers	2.70 y	X-ray	Liquid
Cobalt-57	^{57}Co	Mossbauer spectrometry	270.9 d	β and γ	Metal Foil
Cobalt-60	^{60}Co	Irradiators: sterilization and food preservation	5.27 y	β and γ	Metal (slugs or pellets)
Nickel-63	^{63}Ni	Electron capture detectors	96 y	Β	Metal foil
Germanium-68	^{68}Ge	Positron Emission Tomography (PET) checking	271 d	X-ray and γ (Ga-68 daughter)	Epoxy mixture
Selenium-75	^{75}Se	Industrial radiography	120 d	Γ	Metal compound, pellets
Krypton-85	^{85}Kr	Thickness gauges	10.72 y	β and γ	Gas

17 International Atomic Energy Agency, *Dangerous Quantities of Radioactive Materials (D-Values)*.

18 United States Nuclear Regulatory Commission, "Security Orders and Requirements: Increased Control Requirements (Radionuclides of Concern (Table 1))," last updated May 2, 2016, http://www.nrc.gov/security/byproduct/table1.pdf.

19 International Atomic Energy Agency, *Dangerous Quantities of Radioactive Materials (D-Values)*, Appendix IV.

Table 1. Isotopes Considered as Potential Radiological Weapons (Continued)

Isotope	Symbol	Practice	Half-Life	Radiation Type	Primary Form
Strontium-90	^{90}Sr	Radioisotopic thermo-electric generators (RTGs)	29.1 y	Β	Metal oxide ceramic
Molybdenum-99	^{99}Mo	Diagnostic isotope generators	2.75 d	Β	Metal oxide
Palladium-103	^{103}Pd	Brachytherapy: low dose-rate- eye plaques and permanent implants	17 d	Γ	Resin beads in metal capsule
Ruthenium-106/ Rhodium	$^{106}Ru/Rh$	Brachytherapy: low dose-rate- eye plaques and permanent implants	367 d	Β	Metal Foil
Cadmium-109	^{109}Cd	X ray fluorescence analyzers	453 d	e^- and γ	Metal
Iodine-125	^{125}I	Brachytherapy: low dose-rate	60.1 d	X-ray and γ	Solid/salt
Iodine-131	^{131}I	Medical (unsealed)	8.04 d	β and γ	Solid/salt
Caesium-137	^{137}Cs	Irradiators: sterilization and food preservation	30.17 y	β and γ	Pressed powder
Promethium-147	^{147}Pm	Thickness gauges	2.62 y	Β	Metal
Gadolinium-153	^{153}Gd	Bone densitometry	242 d	β and γ	Solid
Ytterbium-169	^{169}Yb	Industrial radiography	32.0 d	Ε	Metal
Thulium-170	^{170}Tm	Industrial radiography	129 d	Β	Metal
Iridium-192	^{192}Ir	Industrial radiography	74.0 d	β and γ	Metal
Gold-198	^{198}Au	Brachytherapy: low dose rate	2.69 d	Β	Metal
Polonium-210	^{210}Po	Static eliminators	138 d	Α	Metal foil
Radium-226	^{226}Ra	Brachytherapy: low dose rate	1600 y	Α	Salt
Plutonium-238	^{238}Pu	Radioisotopic thermo-electric generators (RTGs)	87.7 y	Α	Metal oxide ceramic
Plutonium-239/ Beryllium	$^{239}Pu/Be$	Calibration sources	24390 y	Ν	Intermetallic compound
Americium-241	^{241}Am	Calibration facilities	432.2 y	α and γ	Pressed ceramic powder (oxide)
Americium-241/ Beryllium	$^{241}Am/Be$	Well logging	432 y	Ν	Compressed powder
Curium-244	^{244}Cm	Thickness gauges	18.1 y	Α	Solid
Californium-252	^{252}Cf	Brachytherapy: low dose rate	2.64 y	Ν	Metal oxide ceramic

Source: Information from International Atomic Energy Agency, *Categorization of Radioactive Sources*, IAEA-TECDOC-1344 (Vienna, Austria: Radiation Safety Section, 2003), http://www-pub.iaea.org/MTCD/publications/pdf/te_1344_web.pdf.

Table 2. Isotopes, Practices, and Their Range of Activities and Categories

Isotope	Practice	Typical Activity in Use for This Practice (TBq)	D-value (TBq)	Ratio A/D	Category
^{3}H	Tritium targets	2.6E-01	2.0E+03	1.3E-04	5
^{32}P	Medical (unsealed)	2.2E-02	1.0E+01	2.2E-03	5
^{55}Fe	X ray fluorescence analyzers	7.4E-04	8.0E+02	9.3E-07	5
^{57}Co	Mossbauer spectrometry	1.9E-03	7.0E-01	2.6E-03	5
^{60}Co	Irradiators: sterilization and food preservation	1.5E+05	3.0E-02	4.9E+06	1
^{63}Ni	Electron capture detectors	3.7E-04	6.0E+01	6.2E-06	5
^{68}Ge	Positron Emission Tomography (PET) checking	1.1E-04	7.0E-01	1.6E-04	5
^{75}Se	Industrial radiography	3.0E+00	2.0E-01	1.5E+01	2
^{85}Kr	Thickness gauges	3.7E-02	3.0E+01	1.2E-03	4
^{90}Sr	Radioisotopic thermoelectric generators (RTGs)	7.4E+02	1.0E+00	7.4E+02	1
^{99}Mo	Diagnostic isotope generators	3.7E-02	3.0E-01	1.2E-01	4
^{103}Pd	Brachytherapy: low dose-rate- eye plaques and permanent implants	1.1E-03	9.0E+01	1.2E-05	5
$^{106}Ru/Rh$	Brachytherapy: low dose-rate eye plaques and permanent implants	2.2E-05	3.0E-01	7.4E-05	5
^{109}Cd	X ray fluorescence analyzers	1.1E-03	2.0E+01	5.6E-05	4
^{125}I	Brachytherapy: low dose-rate	1.9E-02	2.0E-01	9.3E-02	4
^{131}I	Medical (unsealed)	3.7E-03	2.0E-01	1.9E-02	4
^{137}Cs	Irradiators:sterilization and food preservation	1.1E+05	1.0E-01	1.1E+06	1
^{147}Pm	Thickness gauges	1.9E-03	4.0E+01	4.6E-05	4
^{153}Gd	Bone densitometry	3.7E-02	1.0E+00	3.7E-02	4
^{169}Yb	Industrial radiography	1.9E-01	3.0E-01	6.2E-01	2
^{170}Tm	Industrial radiography	5.6E+00	2.0E+01	2.8E-01	2
^{192}Ir	Industrial radiography	3.7E+00	8.0E-02	4.6E+01	2
^{198}Au	Brachytherapy: low dose rate	3.0E-03	2.0E-01	1.5E-02	4
^{210}Po	Static eliminators	1.1E-03	6.0E-02	1.9E-02	4
^{226}Ra	Brachytherapy: low dose rate	5.6E-04	4.0E-02	1.4E-02	4
^{238}Pu	Radioisotopic thermoelectric generators (RTGs)	1.0E+01	6.0E-02	1.7E+02	1
$^{239}Pu/Be$	Calibration sources	1.1E-01	6.0E-02	1.9E+00	3
^{241}Am	Calibration facilities	3.7E-01	6.0E-02	6.2E+00	3
$^{241}Am/Be$	Well logging	7.4E-01	6.0E-02	1.2E+01	3
^{244}Cm	Thickness gauges	1.5E-02	5.0E-02	3.0E-01	4
^{252}Cf	Brachytherapy: low dose rate	3.1E-03	2.0E-02	1.5E-01	3

Source: Information from International Atomic Energy Agency, *Categorization of Radioactive Sources*, IAEA-TECDOC-1344 (Vienna, Austria: Radiation Safety Section, 2003), http://www-pub.iaea.org/MTCD/publications/pdf/te_1344_web.pdf; International Atomic Energy Agency, *Dangerous Quantities of Radioactive Materials (D-Values)*, Emergency Preparedness and Response EPR-D-VALUES 2006 (Vienna, Austria: Radiation and Transport Safety Section, August 2006), Appendix IV, http://www-pub.iaea.org/MTCD/publications/PDF/EPR_D_web.pdf.

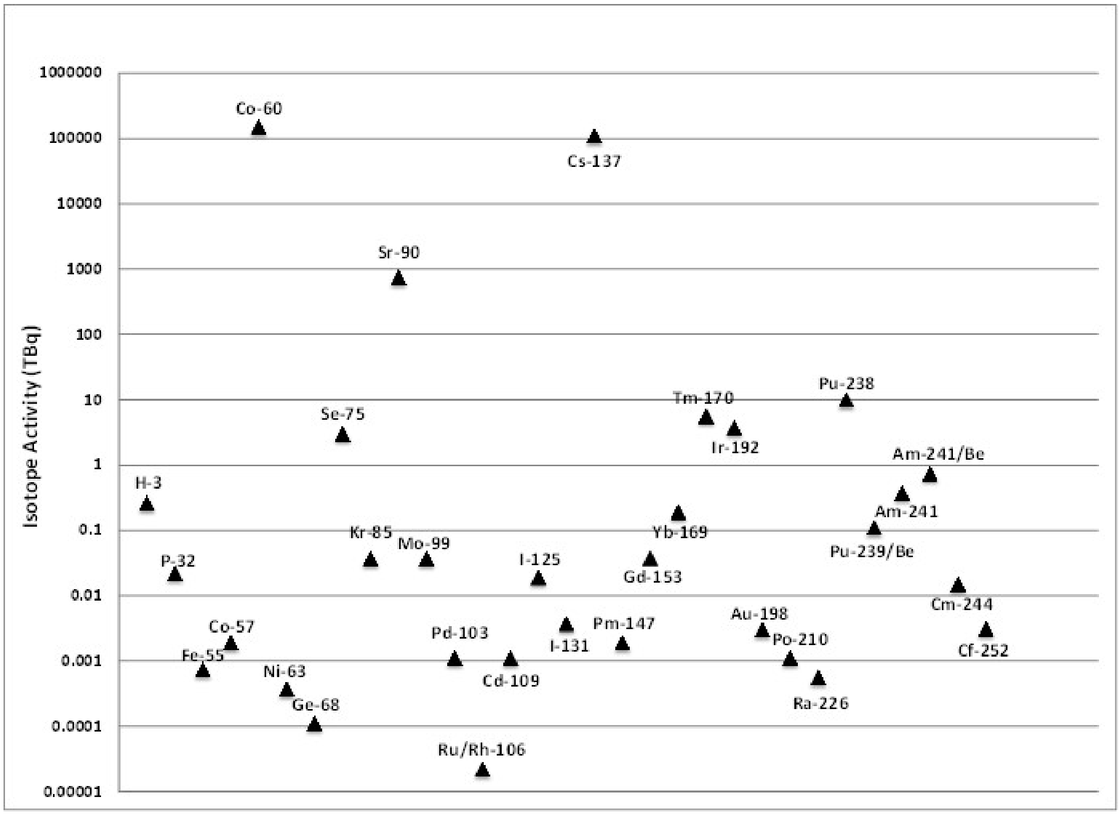

Figure 1. Typical Activities for Isotope Practices

Note: There is no horizontal axis on this and subsequent similar figures. The ordering of the isotopes by atomic mass units is a matter of convenience for the author and reader.

The most significant obstacle facing a non-state actor who is seeking to deploy an RDD is the acquisition of desired radioactive material. Radioactive material is difficult to handle and weaponize and can pose a significant risk to the user. To maintain the security of sources within the United States, the NRC has embodied IAEA guidance within its policy, aimed primarily at the security of Category 1 and 2 sources. However, despite significant advances in securing and recovering large radioactive sources, there are still security concerns. A Government Accountability Office (GAO) inspection of several facilities found notable security flaws due to vague regulations enforced by the NRC.[20] In addition to relaxed security at these facilities, little to no regulation has been imposed on the lower three categories of sources, which could pose an equal—if not greater—threat if aggregated. Domestic orphaned sources also pose a threat. The disposal costs of radioactive materials serve as a disincentive for properly discarding radiological material. It is estimated that one radioactive source goes missing (i.e., "is orphaned") in the United States

[20] *Securing Radiological Materials: Examining the Threat Next Door: Hearing Before the U.S. Senate Comm. On Homeland Security & Governmental Affairs*.

each day.[21] Government programs are in place for recovering orphan sources, but several large sources remain unaccounted for throughout the nation. In addition, budgetary concerns are decreasing the effectiveness of recovery organizations (i.e., their mission is deemed non-vital).

Another avenue for obtaining radioactive material comes from outside the United States. The widespread industrial application of radioactive material provides a large base from which to procure sources. Despite IAEA guidance, many nations still fail to regulate and protect their dangerous sources adequately. For example, in December 2001 in the Georgian Soviet Socialist Republic, an abandoned Russian RTG, which contained significant quantities of ^{90}Sr, was discovered. Three woodsmen encountered the source and unknowingly exposed themselves to high doses of radiation. Two of the woodsmen developed serious symptoms of Acute Radiation Syndrome (ARS) and beta radiation burns that required immediate medical treatment.[22] Another example, from Mexico, occurred when a transport vehicle carrying a significant amount of ^{60}Co was hijacked by criminals.[23] These incidents demonstrate a lack of security and the opportunity that surrounds the acquisition of radiological material. A high demand for illicit radioactive material has resulted in heavy black-market trade, notably in Former Soviet Union (FSU) states. While the acquisition of radioactive material outside of the United States may be easier, border security poses a significant obstacle to covertly bringing this material into the country. Instruments designed to detect radiological material are becoming increasingly sensitive and prolific at entry points into the United States. In addition, the heavy shielding required to hide a radioactive source from detection would increase the size and limit the maneuverability of the source. According to the IAEA Incident and Trafficking Database (ITDB), in 2013, five incidents involved IAEA Category 1–3 radioactive sources, four of which were thefts.[24]

If a state actor that had nuclear reactor technology failed to regulate and protect its dangerous sources adequately, it could supply radioactive material ranging from spent nuclear fuel rods to large quantities of pure radioisotopes. This situation would enable those seeking to engage in radiological warfare to bypass the main obstacle in securing radiological material. However, in most cases, it would not be beneficial for a state to supply radiological material for fear of attribution, reprisal, and/or international condemnation. In

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[21] Charles D. Ferguson et al. *The Four Faces of Nuclear Terrorism* (New York, NY: Routledge, Taylor & Francis Group, 2005), 291.

[22] International Atomic Energy Agency, *The Radiological Accident in Lia, Georgia* (Vienna, Austria: IAEA, 2014), http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1660web-81061875.pdf.

[23] International Atomic Energy Agency, “Mexico Informs IAEA of Theft of Dangerous Radioactive Source,” last updated February 24, 2015, https://www.iaea.org/newscenter/news/mexico-informs-iaea-theft-dangerous-radioactive-source.

[24] International Atomic Energy Agency, “Incident and Trafficking Database (ITDB),” last updated November 5, 2015, http://www-ns.iaea.org/security/itdb.asp.

addition, states that possess nuclear reactors have conventional capabilities at their disposal to produce similar impacts at lower risk and cost.

B. Credibility of Threats

The different types of radiological weapons are categorized by dispersal mechanism or route of exposure and can be evaluated based upon desired impacts, radioisotopes of concern, availability of sources, and a hypothetical event. Using a selection criterion based upon dispersal mechanisms, radiological parameters, the quantities of radioisotope required, commercial availability of sources, security of the sources, and the physical states of the material, a list of radioisotopes of greatest concern was evaluated for each method of dispersal. Figure 2 illustrates this process. Each of the evaluations that follow includes an assessment of the credibility of that radiological weapon as a threat.

For each RDD, radioisotope selection was first categorized by the method of dispersal. Every radioisotope of interest was evaluated for selection for each dispersal mechanism in a specific scenario of use. The next step was to calculate the activity (quantity) of material required to produce the intended effects of the RDD (acute radiation injury, area denial, and so forth) in that scenario.

These activities of concern ("C") were calculated using published dose conversion values. For instance, for the RED, the intended effect is injury to persons exposed in the vicinity of the source. The dose conversion factor used for that estimate is from the IAEA publication The D-values are excerpted from *Dangerous Quantities of Radioactive Materials (D-Values)*,[25] which tabulates dose rate conversion factors for external exposure.

The activity of concern ("C" in TBq) for each radioisotope was then compared against the material contained in industrial sources in commercial practice. For each isotope, the typical activity in use in that practice (in TBq) is defined as the "Activity in Practice" ("P" in TBq). The ratio of P/C is a measure of the inverse of how many sources in commercial practice would be required to produce the intended effects of the RDD. The final step added an analysis of the primary form of the radioisotope (solid, gas, powder, sintered, and so forth) in each source to determine its suitability for dispersion. For example, a solid metallic source would be much more difficult to aerosolize than a powder. From these criteria, an evaluation was made of the suitability of each radioisotope as a radiological threat in the scenario considered.

[25] International Atomic Energy Agency, *Dangerous Quantities of Radioactive Materials (D-Values)*, Appendix IV.

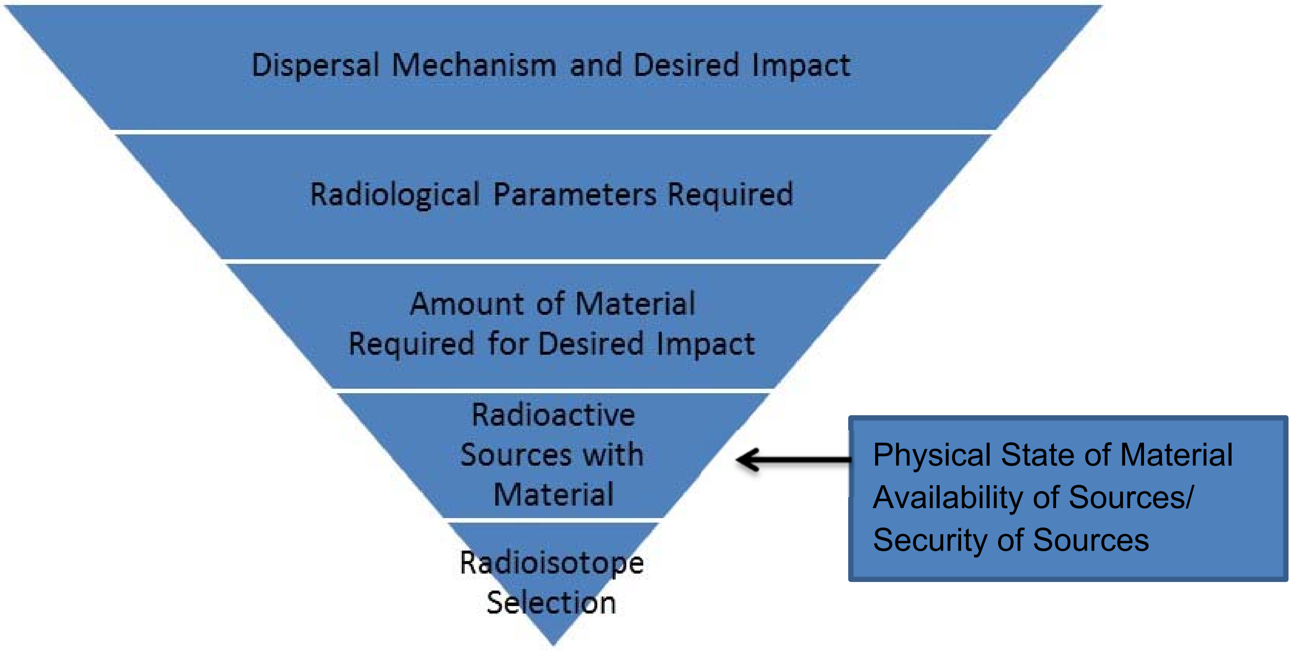

Figure 2. Radiological Agent Selection Process

C. Radiological Threats

1. RED

The simplest radiological threat would be the placement of unshielded radioactive material in a heavily trafficked area as an RED. An RED is designed to stealthily irradiate unshielded people in close vicinity, causing acute radiation injury and creating panic. The threat from an RED relies upon the size and activity of the source and the distance of the subject from the source and the time he/she was exposed to the source. The time between the initial placement of an RED and the correct diagnosis of ARS and discovery of the source drives the scale of impact. While most RED scenarios will not cause significant numbers of prompt casualties, prolonged exposure could result in ARS symptoms. Ranging from mild to lethal, radiation poisoning from single or multiple hidden REDs will cause mass disruption. This outcome can be seen from the overflow of Brazilian hospitals by the "worried well" following a highly publicized case of incidental exposure in Goiânia, Brazil.[26]

Using the same IAEA reference that provides D-values for select radioisotopes, a measure of the hazard posed by an RED is the RBE-weighted dose rate conversion factor for external exposure of the red marrow at 1 m from a source, ((Sv/hr.)/TBq)[27], and can be

[26] International Atomic Energy Agency, *The Radiological Accident in Goiânia*.

[27] International Atomic Energy Agency, *Dangerous Quantities of Radioactive Materials (D-Values)*, 37.

derived from Tables 13 and 15 of the IAEA reference.[28] For simplicity, it is assumed that the dose to the red bone marrow can be used to approximate the dose to all the organs in the torso (i.e., to the whole body).

An RED irradiates subjects without direct contact; therefore, strong gamma- and/or neutron-emitting radioisotopes are required. An example of a plausible RED scenario would be the placement of a 260-TBq source of ^{137}Cs (amount in a typical blood or tissue irradiator) below a subway seat or bench. It would irradiate those commuters in the seat over an extended time period, and the whole-body radiation levels would build up in a person. With a dose equivalent rate conversion factor of 0.035 (Sv/hr.)/TBq at 1 m, it is estimated that a person sitting 1 m away from the source would have to occupy that seat for less than 10 min. to be exposed to greater than 1.25 Sv. Failure to accurately diagnose ARS could result in the source being left undiscovered for a significant amount of time, irradiating many people and potentially leading to more advanced and lethal stages of ARS. This example uses an IAEA Category 1 source, which should be difficult to acquire. Category 1 and 2 sources are more secure than Categories 3–5 but have the potential to irradiate persons in a larger area at much higher doses if placed as an unshielded RED.

Table 3 provides the information useful for identifying the radioactive materials that would be a credible threat as an RED. The first three columns identify the radioisotopes being considered, what activities are typically used in practice ("P"), and conversion factors that convert activity (TBq) to dose equivalent rate (Sv/hr.) at 1 m. For each isotope of interest, the fourth column identifies the "Activity of Concern (C)," which is the activity that would be required to produce the dose rate (or dose) of concern—in this case, acute health effects, which are defined as an effective dose equivalent rate of 1.25 Sv/hr. at 1 m. For each isotope of interest, the fifth column identifies the "P/C" ratio, which is a measure of how effective that isotope would be in this radiological threat. A P/C ratio greater than 1.0 indicates that the activity in a single commercial practice supplies enough radioactive material to produce greater than the desired dose rate (or dose) in this scenario. As a standard for evaluating whether a radioactive material is a credible radiological threat, it is assumed that obtaining 10 sources of the type used in commercial practice is credible, so a P/C ratio of 0.1 or greater (values in bold font) would indicate that that radioactive material likely poses a credible radiological threat in that scenario.

[28] International Atomic Energy Agency, *Dangerous Quantities of Radioactive Materials (D-Values)*, 70–78.

Table 3. RED Radioisotope Selection

Radioisotope Symbol	Activity in Practice (P) (Typical) (TBq)	Dose Equivalent Rate Conversion Factor* (Sv/hr.)/(TBq)	Activity of Concern (C) (TBq/1.25 Sv in 1 Hr.)	P/C Ratio
^{3}H	2.6E-01	1.0E-13	1.2E+13	2.2E-14
^{32}P	2.2E-02	3.0E-04	4.2E+03	5.3E-06
^{55}Fe	7.4E-04	0		
^{57}Co	1.9E-03	5.0E-03	2.5E+02	7.7E-06
^{60}Co	1.5E+05	1.5E-01	8.5E+00	**1.8E+04**
^{63}Ni	3.7E-04	4.3E-10	2.9E+09	1.3E-13
^{68}Ge	1.1E-04	6.1E-02	2.0E+01	5.4E-06
^{75}Se	3.0E+00	2.1E-02	6.0E+01	5.0E-02
^{85}Kr	3.7E-02	1.5E-04	8.1E+03	4.6E-06
^{90}Sr	7.4E+02	8.6E-04	1.4E+03	**5.1E-01**
^{99}Mo	3.7E-02	1.4E-02	8.9E+01	4.2E-04
^{103}Pd	1.1E-03	1.7E-05	7.2E+04	1.5E-08
$^{106}Ru/Rh$	2.2E-05	1.5E-02	8.1E+01	2.7E-07
^{109}Cd	1.1E-03	1.2E-04	1.1E+04	1.0E-07
^{125}I	1.9E-02	7.6E-05	1.7E+04	1.1E-06
^{131}I	3.7E-03	2.2E-02	5.6E+01	6.6E-05
^{137}Cs	1.1E+05	3.5E-02	3.6E+01	**3.0E+03**
^{147}Pm	1.9E-03	4.0E-07	3.2E+06	6.0E-10
^{153}Gd	3.7E-02	2.2E-03	5.8E+02	6.4E-05
^{169}Yb	1.9E-01	1.1E-02	1.2E+02	1.6E-03
^{170}Tm	5.6E+00	1.5E-04	8.1E+03	6.9E-04
^{192}Ir	3.7E+00	4.7E-02	2.7E+01	**1.4E-01**
^{198}Au	3.0E-03	2.4E-02	5.2E+01	5.8E-05
^{210}Po	1.1E-03	5.0E-07	2.5E+06	4.4E-10
^{226}Ra	5.6E-04	1.0E-01	1.2E+01	4.7E-05
^{238}Pu	1.0E+01	1.1E-06	1.2E+06	8.6E-06
$^{239}Pu/Be^{\dagger}$	1.1E-01	1.8E-03	6.9E+02	1.6E-04
^{241}Am	3.7E-01	3.3E-04	3.8E+03	9.7E-05
$^{241}Am/Be^{\dagger}$	7.4E-01	1.8E-03	6.9E+02	1.1E-03
^{244}Cm	1.5E-02	7.2E-07	1.7E+06	8.6E-09
^{252}Cf	3.1E-03	4.0E-01	3.2E+00	9.8E-04

* RBE-weighted dose rate in the red marrow at a distance of 1 m from the source.

† The activity given is that of the alpha-emitting radioisotopes (e.g., ^{239}Pu or ^{241}Am. Doses from low linear energy transfer (LET) and high LET radiation were taken into account and summed.

Note: A P/C ratio of 0.1 or greater (values in bold font) indicate that that radioactive material likely poses a credible radiological threat in that scenario.

The IAEA estimates the RBE-weighted dose equivalent rate conversion factor for external exposure of the red marrow at 1 m from a source for ^{55}Fe to be zero (0.0)[29]; therefore, this isotope is not a viable candidate to be used in an RED. From the P/C ratio in Table 3, the typical activity in commercial practice would provide less than 0.001 (1/1,000) of the dose rate of 1.25 Sv/hr. for devices that use ^{3}H, ^{32}P, ^{57}Co, ^{63}Ni, ^{68}Ge, ^{85}Kr, ^{99}Mo, ^{103}Pd, ^{106}Ru/Rh, ^{109}Cd, ^{125}I, ^{131}I, ^{147}Pm, ^{153}Gd, ^{170}Tm, ^{198}Au, ^{210}Po, ^{226}Ra, ^{238}Pu, ^{239}Pu/Be, ^{241}Am, ^{244}Cm, or ^{252}Cf; therefore, these isotopes are not credible candidates to be used in an RED. From Table 3, the typical activity in commercial practice would provide greater than 0.001 but less than 0.1 (1/10) of the dose rate of 1.25 Sv/hr. for devices that use ^{75}Se, ^{169}Yb, or ^{241}Am/Be; therefore, these isotopes are also unlikely to be credible candidates to be used in an RED. (In this scenario, note that ^{75}Se has a P/C ratio of 0.05. While not within the criterion of 0.1 or greater, 0.05 is close to that value and much closer than any other isotope considered as credible radiological weapons. It is left to the judgement of the reader to choose whether to consider ^{75}Se as a "likely" credible threat agent.) From the original 31 isotopes considered as potentially dangerous by the IAEA, that leaves 4 isotopes—^{60}Co, ^{90}Sr, ^{137}Cs, and ^{192}Ir—as credible candidates to be used in an RED. Figure 3 illustrates this arrangement of the credibility of different radioisotopes as RED threats. In this figure, those radioisotopes with P/C ratios less than 0.001 are highlighted in green, those radioisotopes with P/C ratios greater than 0.001 but less than 0.1 (1/10) are highlighted yellow, and those radioisotopes with P/C ratios greater than 0.1 are highlighted in red. This color scheme, which emphasizes those radioisotopes that could pose a credible threat in this scenario, is carried through in this analysis for each of the figures for the subsequent scenarios.

The low technological expertise required, significant pool of viable radioisotopes, and practical number of sources containing those radioisotopes make RED construction and deployment a possibility. In addition, these sources may not be as well secured as others and might be obtained with medium effort. Combined with the likelihood of causing acute radiation injury among a limited population and sowing panic, an RED poses a credible threat for this scenario.

[29] Ibid.

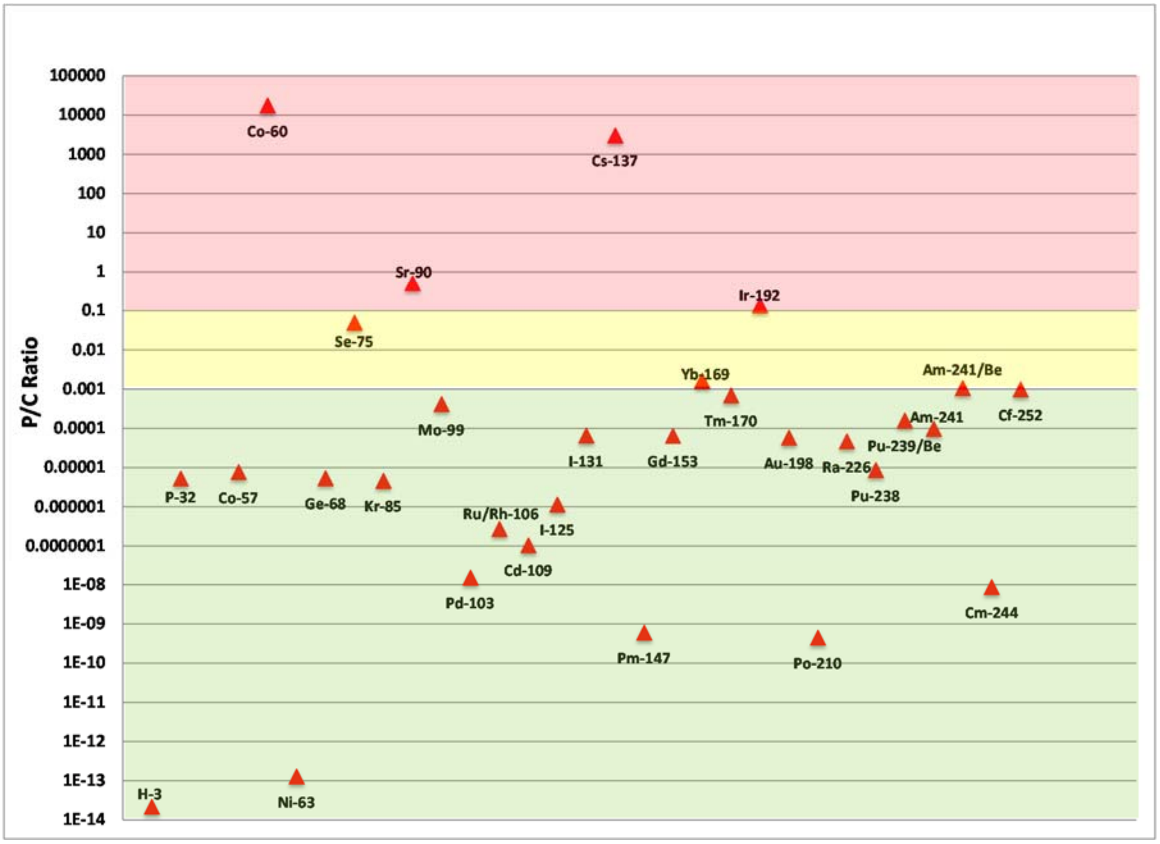

Figure 3. Radiological Exposure Device (RED) P/C Ratios

Note 1: There is no horizontal axis on this figure. The ordering of the isotopes by atomic mass units is a matter of convenience for the author and reader.

Note 2: Radioisotopes with P/C ratio less than 0.001 are highlighted in green, radioisotopes with P/C ratios greater than 0.001 but less than 0.1 (1/10) are highlighted in yellow, and radioisotopes with P/C ratios greater than 0.1 are highlighted in red.

2. Explosive RDD

An explosive RDD would require more technical expertise (in explosives) than an RED, but recent widespread use of improvised explosive devices (IEDs) has shown this dispersal method to be a viable option for non-state actors. An explosive RDD combines the explosive force of an IED with radioactive material. The explosive disperses the radioactive material over a wide area. It is designed to instill panic and has the added benefit of performing an area denial function. In addition, self-evacuation and the plume of aerosolized particles could increase contamination beyond just the blast zone. However, due to the wide dispersal of radioactive material, it is less likely that any one location will have a concentration that is high enough to cause acute radiation injury. In fact, it is reasonable to assume that the explosive blast and shrapnel will produce more immediate casualties than the ionizing effects of dispersed radioactive material. Therefore, the impact of this weapon is mostly limited to area denial and acts as an impact multiplier (psychologically) for IEDs.

(As discussed previously, this paper will use the NRC standard of 0.02 mSv per hour[30] as the standard above which an area would be regarded as radioactively contaminated.)

Explosive RDD threats range anywhere from a backpack bomb laced with a few terabecquerels of radioactive material to a truck packed with high explosives and thousands of terabecquerels of radioactive material. Even the smallest of IEDs can be turned into radiological weapons that result in far greater impacts. Senator Carper posed the following hypothetical situation: "If the Boston Marathon terrorists had turned their pressure-cooker bombs into dirty bombs, then the consequences of that tragic day could have multiplied by an order of magnitude."[31] The explosion of an explosive RDD will immediately alert authorities of the attack, and the radiological component of the event will be recognized early. However, contamination will be widespread and may be compounded by radioactive particles in the air and by those tracked by self-evacuated victims and first responders. Cutaneous contamination will pose an obstacle to medical care since casualties of the blast will require decontamination before being able to receive treatment.

Area denial can be accomplished by contamination of the ground surface by almost any radioactive material. The U.S. Environmental Protection Agency (EPA) has published reference values for external exposure to isotopes in air, water, and soil.[32] Table III.3 of that publication provides the coefficients that can be used to estimate the effective dose equivalent rate from exposure to a contaminated ground surface ((Sv/hr.)/(TBq/m^2)).[33] Explosive RDDs require large amounts of radioactive material to be dispersed over a wide area; therefore, the quantity of radioactive material and security (availability) of sources are the most important contributing factors to radioisotope selection.

The degree to which a radioisotope will offer a long-term threat and require decontamination is directly proportional to the specific activity and half-life of the isotope of interest. ^{137}Cs is a strong gamma emitter that could fulfill a significant area denial function in an explosive RDD and make it difficult to respond to the incident without appropriate protection. Sources for large explosive RDDs are anticipated to be mostly Category 1, such as RTGs, food or tissue irradiators, and teletherapy and brachytherapy sources. However, small-to-medium sized explosive RDDs could employ aggregated Category 4 to Category 2 sources, such as industrial gauges or low dose-rate brachytherapy devices. ^{90}Sr is a beta

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30 United States Nuclear Regulatory Commission, "Subpart D--Radiation Dose Limits for Individual Members of the Public."

31 *Securing Radiological Materials: Examining the Threat Next Door: Hearing Before the U.S. Senate Comm. On Homeland Security & Governmental Affairs*.

32 Keith F. Eckerman and Jeffrey C. Ryman, *External Exposure to Radionuclides in Air, Water, and Soil*, Federal Guidance Report No. 12, EPA-402-R-93-081 (Oak Ridge, TN: Oak Ridge National Laboratory, 1993). https://crpk.ornl.gov/documents/fgr12.pdf.

33 Ibid., 93–109.

emitter that, while of more limited range, would still pose a contamination challenge and required cutaneous and respiratory protection. ^{90}Sr is capable of causing cutaneous harm and is available in large sources, such as RTGs. The low security of these sources (orphaned sources in FSU nations) makes them a prime candidate for a medium- or large-sized explosive RDD.

An example of a plausible explosive RDD scenario, similar to that for the RED, is the explosive dispersal of a 110,000-TBq source of ^{137}Cs (amount in a typical irradiator used for sterilization and food preservation) over an area of 10,000 m^2 (a radius of about 56.5 m). Assuming that the ^{137}Cs is uniformly distributed over the surface (0.0019 TBq/m^2), this contamination would result in a dose rate of about 0.11 Sv/hr. at 1 m above the contaminated area, which is not sufficient to produce acute radiation injury but is well above the rate permitted by the NRC for unrestricted access to the area (0.02 mSv/hr.). This example uses an IAEA Category 1 source, which should be difficult to acquire. Category 1 and 2 sources are more secure than Categories 3–5 but have the potential to irradiate persons in a larger area at much higher doses if used in an explosive RDD.

Table 4 provides the information useful for identifying the radioactive materials that would be a credible threat as an explosive RDD. The first three columns identify the radioisotopes being considered, what activities are typically used in practice ("P") and conversion factors that convert activity per unit area (TBq/m^2) to dose equivalent rate (Sv/hr.). For each isotope of interest, the fourth and fifth columns identify the "Activity of Concern (C)" and the P/C Ratio for acute health effects, which are defined as an effective dose equivalent rate of 1.25 Sv/hr. over 10,000 m^2. In recognition that an explosive RDD may not produce acutely hazardous radiation levels but can result in significant contamination, the sixth and seventh columns identify the "Activity of Concern (C)" that would be required to produce an effective dose equivalent rate of 0.02 mSv/hr. over 10,000 m^2 and the associated P/C ratios.

The EPA estimates the coefficients to estimate the effective dose equivalent rate from exposure to a contaminated ground surface for ^{3}H, ^{55}Fe, and ^{63}Ni, to be zero (0.0)[34]; therefore, these isotopes are not viable candidates to be used in an explosive RDD. From the P/C ratios in Table 4, the typical activity in commercial practice would provide less than 0.001 (1/1,000) of the dose rate of 1.25 Sv/hr. from 10,000 m^2 of a contaminated surface for devices that use ^{32}P, ^{57}Co, ^{68}Ge, ^{75}Se, ^{85}Kr, ^{90}Sr, ^{99}Mo, ^{103}Pd, $^{106}Ru/Rh$, ^{109}Cd, ^{125}I, ^{131}I, ^{147}Pm, ^{153}Gd, ^{169}Yb, ^{170}Tm, ^{192}Ir, ^{198}Au, ^{210}Po, ^{226}Ra, ^{238}Pu, $^{239}Pu/Be$, ^{241}Am, $^{241}Am/Be$, ^{244}Cm or ^{252}Cf; therefore, these isotopes are not credible candidates to be used in an explosive RDD.

[34] Ibid.

Table 4. Explosive RDD Radioisotope Selection

			Acute Health Effects (1.25 Sv/hr. over 10,000 m^2)		Area Denial Effects (0.02 mSv/hr. over 10,000 m^2)	
Radio-Isotope Symbol	Activity in Practice (P) (Typical) (TBq)	Dose Equivalent Coefficient* (Sv/hr.)/(TBq/m^2)	Activity of Concern (C) (TBq)	P/C Ratio	Activity of Concern (C) (TBq)	P/C Ratio
^{3}H	2.60E-01	N/A 0	N/A	N/A	N/A	N/A
^{32}P	2.20E-02	1.05E-02	1.19E+06	1.84E-08	1.91E+01	1.15E-03
^{55}Fe	7.40E-04	N/A	N/A	N/A	N/A	N/A
^{57}Co	1.90E-03	4.14E-01	3.02E+04	6.29E-08	4.83E-01	3.93E-03
^{60}Co	1.50E+05	8.46E+00	1.48E+03	**1.02E+02**	2.36E-02	**6.35E+06**
^{63}Ni	3.70E-04	N/A	N/A	N/A	N/A	N/A
^{68}Ge	1.10E-04	7.78E-05	1.61E+08	6.84E-13	2.57E+03	4.28E-08
^{75}Se	3.00E+00	1.36E+00	9.21E+03	3.26E-04	1.47E-01	**2.04E+01**
^{85}Kr	3.70E-02	9.50E-03	1.32E+06	2.81E-08	2.10E+01	1.76E-03
^{90}Sr	7.40E+02	1.02E-03	1.22E+07	6.05E-05	1.96E+02	**3.78E+00**
^{99}Mo	3.70E-02	5.29E-01	2.36E+04	1.57E-06	3.78E-01	**9.79E-02**
^{103}Pd	1.10E-03	3.92E-02	3.19E+05	3.45E-09	5.10E+00	2.16E-04
^{106}Ru/Rh	2.20E-05	7.63E-01	1.64E+04	1.34E-09	2.62E-01	8.40E-05
^{109}Cd	1.10E-03	8.10E-02	1.54E+05	7.13E-09	2.47E+00	4.46E-04
^{125}I	1.90E-02	1.54E-01	8.13E+04	2.34E-07	1.30E+00	**1.46E-02**
^{131}I	3.70E-03	1.35E+00	9.23E+03	4.01E-07	1.48E-01	**2.50E-02**
^{137}Cs	1.10E+05	1.03E-03	1.22E+07	9.03E-03	1.95E+02	**5.64E+02**
^{147}Pm	1.90E-03	1.23E-04	1.02E+08	1.87E-11	1.63E+03	1.17E-06
^{153}Gd	3.70E-02	3.82E-01	3.28E+04	1.13E-06	5.24E-01	**7.06E-02**
^{169}Yb	1.90E-01	1.09E+00	1.14E+04	1.66E-05	1.83E-01	**1.04E+00**
^{170}Tm	5.60E+00	2.13E-02	5.88E+05	9.53E-06	9.40E+00	**5.96E-01**
^{192}Ir	3.70E+00	2.89E+00	4.32E+03	8.56E-04	6.92E-02	**5.35E+01**
^{198}Au	3.00E-03	1.44E+00	8.66E+03	3.46E-07	1.39E-01	**2.17E-02**
^{210}Po	1.10E-03	2.98E-05	4.19E+08	2.63E-12	6.70E+03	1.64E-07
^{226}Ra	5.60E-04	2.32E-02	5.39E+05	1.04E-09	8.63E+00	6.49E-05
^{238}Pu	1.00E+01	3.02E-03	4.14E+06	2.41E-06	6.63E+01	**1.51E-01**
^{239}Pu/Be†	1.10E-01	1.32E-03	9.46E+06	1.16E-08	1.51E+02	7.27E-04
^{241}Am	3.70E-01	9.90E-02	1.26E+05	2.93E-06	2.02E+00	**1.83E-01**
^{241}Am/Be†	7.40E-01	9.90E-02	1.26E+05	5.86E-06	2.02E+00	**3.66E-01**
^{244}Cm	1.50E-02	3.16E-03	3.95E+06	3.79E-09	6.33E+01	2.37E-04
^{252}Cf	3.10E-03	2.60E-03	4.81E+06	6.45E-10	7.69E+01	4.03E-05

* Derived from Table III.3 of Federal Guidance Report No. 12.[35]

† The activity given is that of the alpha-emitting radioisotopes (e.g., ^{239}Pu or ^{241}Am).

Note: A P/C ratio of 0.1 or greater **(values in bold font)** indicate that that radioactive material likely poses a credible radiological threat in that scenario.

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[35] Eckerman and Ryman, *External Exposure to Radionuclides in Air, Water, and Soil*, 93–109.

From Table 4, the typical activity in commercial practice would provide greater than 0.001 but less than 0.1 (1/10) of the dose rate of 1.25 Sv/hr. from 10,000 m^2 of a contaminated surface for devices that use ^{137}Cs; therefore, this isotope is also unlikely to be a credible candidate to be used in an explosive RDD. Without regard to the physical form or to the engineering challenges associated with dispersing these isotopes, from the original 31 isotopes considered as potentially dangerous by the IAEA, that leaves 1 isotope—^{60}Co—that could be considered as a potentially credible candidate to be used in an explosive RDD to produce a significant dose rate over a wide area. Figure 4 illustrates this arrangement of the credibility of different radioisotopes as explosive RDD threats for acute whole-body dose.

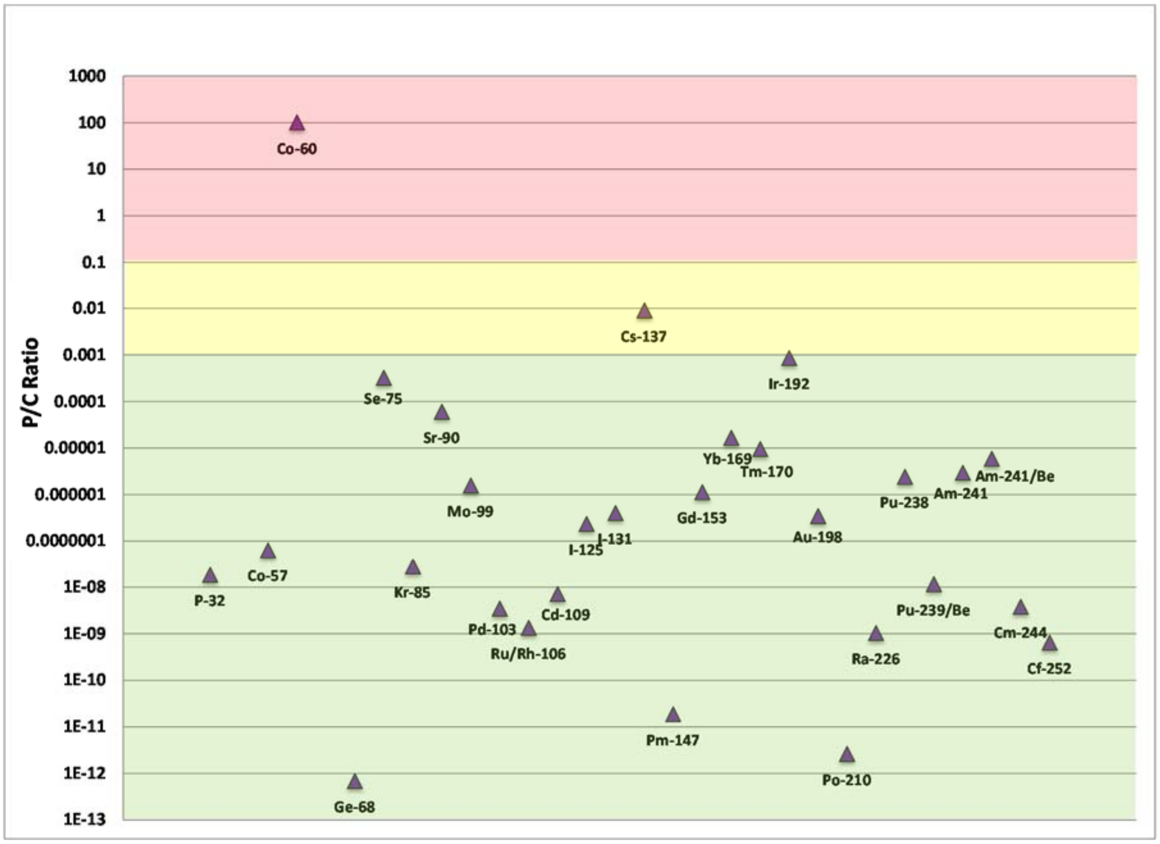

Figure 4. Explosive RDD Radioisotope Selection Based Upon P/C Ratios for Whole-Body Acute Effects

Note 1: There is no horizontal axis on this figure. The ordering of the isotopes by atomic mass units is a matter of convenience for the author and reader.

Note 2: Radioisotopes with P/C ratios less than 0.001 are highlighted in green, the radioisotope with a P/C ratio greater than 0.001 but less than 0.1 (1/10) is highlighted in yellow, and the radioisotope with a P/C ratio greater than 0.1 is highlighted in red.

Another important factor in the selection process is the primary form of the radioactive materials. For example, ^{137}Cs is most commonly found as a powdered salt (cesium chloride (CsCl)) in industrial sources. A powder employed in an explosive RDD would aerosolize and widely disperse the radioactive material. Other materials such as ^{60}Co are typically cast as a solid metal rod, complete with heavy shielding when stored to protect against gamma radiation. Solid metals in an explosive RDD will mostly end up as radioactive shrapnel with as little as 20% of the material aerosolized and dispersed.[36] For this reason, only materials that can be expected to widely disperse as fine particles will be considered as credible candidates for components of an explosive RDD. Table 1 identifies the physical form of the isotopes considered.

Among the remaining isotopes of interest, ^{60}Co consists of metal slugs or pellets and is of a form (metal) that would be unlikely to disperse widely as a fine powder. It is, therefore, unlikely to be a credible candidate to be used in an explosive RDD. That leaves only one isotope—^{137}Cs—as a credible (although unlikely) candidate to be used in an explosive RDD to produce acute health effects.

From the isotopes listed in Table 4, it is clear that very few of the isotopes considered would be expected to contaminate a large area at a level acutely hazardous to health when used in an explosive RDD. However, much less material is required to contaminate the area to a level that would limit access and result in at least some level of area denial. Comparing the relative dose rates (1.25 Sv/hr. to 0.02 mSv/hr.), it is clear that only about 1.6×10^{-5} of the material needed to cause acute health effects would be needed for area denial. When area denial is considered rather than acute health effects, without regard to the physical form or to the engineering challenges associated with dispersing these isotopes, from the original 31 isotopes considered as potentially dangerous by the IAEA, only 10 isotopes—^{60}Co, ^{75}Se, ^{90}Sr, ^{137}Cs, ^{169}Yb, ^{170}Tm, ^{192}Ir, ^{238}Pu, ^{241}Am, and ^{241}Am/Be—could be considered as potentially credible candidates to be used in an explosive RDD to produce a significant dose rate over a wide area. This arrangement of the credibility of different radioisotopes as explosive RDD threats for aerial denial is illustrated in Figure 5. Of these, ^{60}Co (metal slugs or pellets), ^{75}Se (metal compound or pellets), ^{169}Yb (metal), ^{170}Tm (metal), and ^{192}Ir (metal), are of a form (metal) that would be unlikely to disperse widely as a fine powder; therefore, these isotopes are unlikely to be credible candidates to be used in an explosive RDD. ^{241}Am/Be is a compressed powder that, when intact, acts as a neutron source. When explosively dispersed it is assumed that the radiation is due solely to the ^{241}Am. That still leaves five isotopes—^{90}Sr, ^{137}Cs, ^{238}Pu, ^{241}Am, and ^{241}Am/Be—as credible candidates to be used in an explosive RDD to produce area denial effects.

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36 Frederick T. Harper, Steven V. Musolino, and William B. Wente, "Realistic Radiological Dispersal Device Hazard Boundaries and Ramifications for Early Consequence Management Decisions," *Health Physics* 93, no. 1 (July 2007): 1–16, http://www.ncbi.nlm.nih.gov/pubmed/17563488.

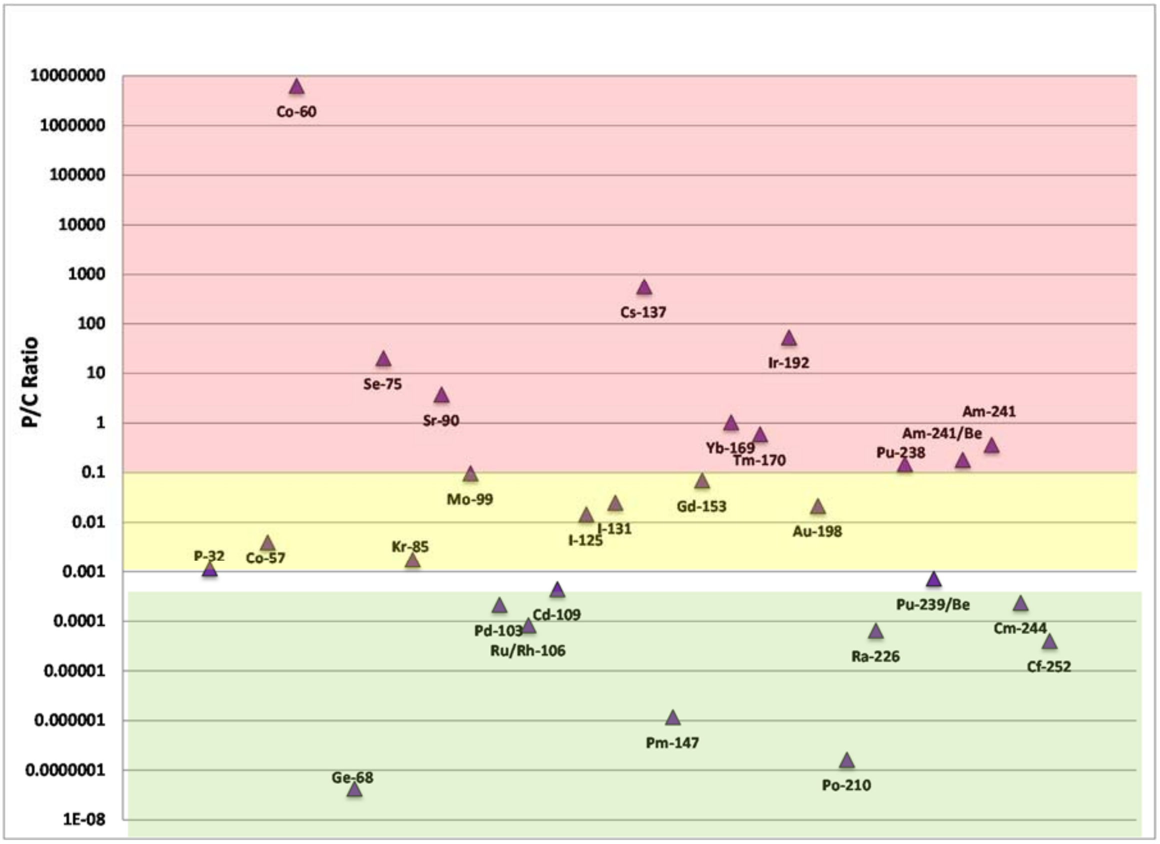

Figure 5. Explosive RDD Radioisotope Selection Based Upon P/C Ratios for Area Denial

Note 1: There is no horizontal axis on this figure. The ordering of the isotopes by atomic mass units is a matter of convenience for the author and reader.

Note 2: Radioisotopes whose P/C ratio is less than 0.001 are highlighted in green, radioisotopes with P/C ratios greater than 0.001 but less than 0.1 (1/10) are highlighted in yellow, and radioisotopes with P/C ratios greater than 0.1 are highlighted in red.

The threat against military targets is low because of mitigating factors such as early detection, training, recognition, response, and security. The military is assumed to be more prepared to deal with the effects of a radiological attack than its civilian counterparts. Civilian targets will be more susceptible to disruption that results in economic losses, area denial, public hysteria, media recognition, and so forth. Explosive RDD construction is relatively simple, relying upon IED technology and the acquisition of radioactive materials. Sources will most likely be domestically acquired if they are readily available, and the process bypasses increasingly robust detection capabilities at the borders. The impact will not be in casualties (likely more people will die from blast than from radiation complications) but in economic disruption and area denial. For these reasons, an explosive RDD is a considerable a credible threat.

3. Aerosol RDD

Dispersing radioactive material as an aerosol requires significant technical knowledge. "An inhalation attack, sometimes called a smoky bomb, would use radio-isotopes that can be burned, vaporized or aerosolized and in a confined space could contaminate the air and be inhaled."[37] Other methods of aerial dispersal require the malicious actor to transform the radioactive material into a small particle capable of being suspended in the air and inhaled. In addition, much more material would be required to cause acute radiation injury since an aerosol greatly disperses the material. Methods of dispersal include using a small airplane (i.e., crop duster), rigging a pesticide sprayer to a vehicle, or introducing radioactive aerosol into the air conditioning system of an enclosed building. The advantages of aerosol dispersal include improving the ability to control where and how much of the isotope is released and improving the potential for a covert release.

Dispersing radioactive material as an aerosol results in multiple potential pathways for radiation exposure: cutaneous and whole-body irradiation from immersion in the cloud of radioactive material external to the body; cutaneous irradiation from contamination that deposits on the skin; and inhalation of radioactive materials that results in irradiation to the respiratory tract and surrounding tissue. Because of the close contact to the skin and the potential for internal contamination, alpha and beta radiation emitters could pose a significant hazard from this dispersion method. Radioisotopes such as ^{137}Cs, ^{90}Sr, ^{238}Pu, ^{226}Ra, and ^{241}Am would require some method of aerosolizing—a task as simple as dilution in water for soluble forms or a daunting technological obstacle requiring a high level of technical expertise (and/or hazard) for non-soluble materials. Aerosol RDDs require large amounts of radioactive material to be dispersed within a large volume; therefore, the quantity of radioactive material and security (availability) of sources are significant contributing factors in radioisotope selection.

The EPA has published reference values for external exposure to isotopes in air, water, and soil.[38] Table III.1 of that publication provides the coefficients that can be used to derive the estimate of the effective dose equivalent rate to the whole body and to the skin from submersion in air contaminated with radioactive material ((Sv/hr.)/(TBq/m^3)).[39] The IAEA has published reference values for exposure to radioactive materials in a variety of scenarios, including non-dispersed material (such as a point source for an RED) and inhalation, ingestion, contamination, and immersion from dispersed radioactive materials.[40] Table 18 of that publication provides the coefficients that can be used to derive the

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[37] Peter D. Zimmerman, James M. Acton, and M. Brooke Rogers, "Seize the Cesium," *The New York Times*, August 1, 2007, http://www.nytimes.com/2007/08/01/opinion/01zimmerman.html?_r=0.

[38] Eckerman and Ryman, *External Exposure to Radionuclides in Air, Water, and Soil*.

[39] Ibid., 57–73.

[40] International Atomic Energy Agency, *Dangerous Quantities of Radioactive Materials (D-Values)*.

estimate of the effective dose equivalent rate to the whole body (red bone marrow) or respiratory tract from inhalation (Sv/TBq).[41] Table 19 of that publication provides the coefficients that can be used to derive the estimate of the effective dose equivalent rate to the skin from contamination ((Sv/hr./(TBq/m^2)).[42]

An example of a plausible aerosol RDD scenario, similar to that for the explosive RDD, is the dispersal of a 260-TBq source of ^{137}Cs (amount in a typical blood or tissue irradiator) into a volume of 30,000 m^3, approximately the volume of a (rather modest) five-story building (each story = 3.3 m (10 ft.) high, 60 m (200 ft.) long, and 30 m (100 ft.) wide). Assuming that the ^{137}Cs is uniformly distributed over the volume (0.0078 TBq/m^3), submersion in this cloud of material would result in a dose rate of about 0.27 Sv/hr. to the skin, or an effective whole-body dose rate of 0.24 mSv/hr. Inhalation of ^{137}Cs at this concentration (0.015 m^3/min. for 90 min., 0.0078 TBq) would result in a dose of about 5.9 Sv to the respiratory tract or 6.2 Sv to the whole body (bone marrow). If the ^{137}Cs in the air uniformly settles onto the horizontal surfaces (0.029 TBq/m^2), including skin, it would result in a dose rate of about 1.4 Sv/hr. to the skin. This example uses an IAEA Category 1 source, which should be difficult to acquire. Category 1 and 2 sources are more secure but have the potential to disperse contamination within a larger volume or at a higher concentration level if used in an aerosol RDD.

Table 5 provides the information useful for identifying the radioactive materials that would be a credible threat as an aerosol RDD, based upon dose from submersion in contaminated air. The first two columns identify the radioisotopes being considered and what activities are typically used in practice ("P"). Two sensitive organs—the whole body and the skin—are considered. A separate evaluation is required for the whole-body dose and the cutaneous dose from submersion in the contaminated air. The third and sixth columns provide the dose conversion factors that convert activity per unit volume (TBq/m^3) to dose equivalent rate (Sv/hr.) for the whole body (Column 3) and skin (Column 6). The fourth and seventh columns identify the "Activity of Concern (C)" that would be required to produce an effective dose equivalent rate of 1.25 Sv/hr. when uniformly mixed into a volume of 30,000 m^3 for the whole body (Column 4) and skin (Column 7). The fifth and eighth columns of Table 5 provide the associated P/C ratios.

The EPA estimates the coefficients for the effective dose equivalent rate to the whole body and skin from submersion in a (semi-infinite cloud) of contaminated air for ^{3}H (skin dose only), ^{55}Fe, and ^{63}Ni, to be zero (0.0)[43]; therefore, these isotopes are not credible candidates to be used in an aerosol RDD.

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[41] Ibid., 83–93.

[42] Ibid., 94–102.

[43] Ibid.

Table 5. Aerosol RDD Radioisotope Selection Based Upon Dose from Submersion in Contaminated Air

		Whole Body			Skin		
Radio-isotope Symbol	Activity in Practice (P) (Typical) (TBq)	Effective Dose Equivalent Coefficient (Sv/hr.)/ (TBq/m3)*	Activity of Concern (C) (TBq in 30,000 m^3 1.25 Sv/hr.)	P/C Ratio	Effective Dose Equivalent Coefficient (Sv/hr.)/ (TBq/m3)	Activity of Concern (C) (TBq in 30,000 m^3 1.25 Sv/hr.)*	P/C Ratio
^{3}H	2.60E-01	1.19E-03	3.15E+07	8.26E-09	0.00E+00	N/A	N/A
^{32}P	2.20E-02	3.56E-01	1.05E+05	2.09E-07	1.62E+02	2.32E+02	9.48E-05
^{55}Fe	7.40E-04	0.00E+00	N/A	N/A	0.00E+00	N/A	N/A
^{57}Co	1.90E-03	2.02E+01	1.86E+03	1.02E-06	2.39E+01	1.57E+03	1.21E-06
^{60}Co	1.50E+05	4.54E+02	8.27E+01	**1.81E+03**	5.22E+02	7.18E+01	**2.09E+03**
^{63}Ni	3.70E-04	0.00E+00	N/A	N/A	0.00E+00	N/A	N/A
^{68}Ge	1.10E-04	2.65E-04	1.41E+08	7.78E-13	2.38E-02	1.57E+06	6.99E-11
^{75}Se	3.00E+00	6.66E+01	5.63E+02	5.33E-03	7.78E+01	4.82E+02	6.22E-03
^{85}Kr	3.70E-02	4.28E-01	8.75E+04	4.23E-07	4.75E+01	7.89E+02	4.69E-05
^{90}Sr	7.40E+02	2.71E-02	1.38E+06	5.35E-04	3.31E+01	1.13E+03	**6.54E-01**
^{99}Mo	3.70E-02	2.62E+01	1.43E+03	2.59E-05	1.13E+02	3.32E+02	1.12E-04
^{103}Pd	1.10E-03	2.76E-01	1.36E+05	8.11E-09	1.40E+00	2.67E+04	4.12E-08
^{106}Ru/Rh†	2.20E-05	3.74E+01	1.00E+03	2.20E-08	3.92E+02	9.56E+01	2.30E-07
^{109}Cd	1.10E-03	1.06E+00	3.54E+04	3.10E-08	3.58E+00	1.05E+04	1.05E-07
^{125}I	1.90E-02	1.88E+00	2.00E+04	9.52E-07	5.00E+00	7.49E+03	2.54E-06
^{131}I	3.70E-03	6.55E+01	5.72E+02	6.46E-06	1.07E+02	3.50E+02	1.06E-05
^{137}Cs	1.10E+05	2.79E-02	1.35E+06	8.17E-02	3.11E+01	1.21E+03	**9.11E+01**
^{147}Pm	1.90E-03	2.49E-03	1.50E+07	1.26E-10	2.92E+00	1.28E+04	1.48E-07
^{153}Gd	3.70E-02	1.34E+01	2.81E+03	1.32E-05	1.80E+01	2.08E+03	1.78E-05
^{169}Yb	1.90E-01	4.64E+01	8.07E+02	2.35E-04	6.23E+01	6.02E+02	3.16E-04
^{170}Tm	5.60E+00	8.03E-01	4.67E+04	1.20E-04	6.52E+01	5.76E+02	9.73E-03
^{192}Ir	3.70E+00	1.41E+02	2.66E+02	1.39E-02	1.99E+02	1.88E+02	1.96E-02
^{198}Au	3.00E-03	6.98E+01	5.37E+02	5.59E-06	1.47E+02	2.55E+02	1.18E-05
^{210}Po	1.10E-03	1.50E-03	2.50E+07	4.39E-11	1.73E-03	2.17E+07	5.08E-11
^{226}Ra	5.60E-04	1.13E+00	3.31E+04	1.69E-08	1.72E+00	2.17E+04	2.58E-08
^{238}Pu	1.00E+01	1.76E-02	2.13E+06	4.68E-06	1.47E-01	2.55E+05	3.93E-05
^{239}Pu/Be‡	1.10E-01	1.53E-02	2.46E+06	4.48E-08	6.70E-02	5.60E+05	1.96E-07
^{241}Am	3.70E-01	2.94E+00	1.27E+04	2.91E-05	4.61E+00	8.14E+03	4.55E-05
^{241}Am/Be‡	7.40E-01	2.94E+00	1.27E+04	5.81E-05	4.61E+00	8.14E+03	9.09E-05
^{244}Cm	1.50E-02	1.77E-02	2.12E+06	7.07E-09	1.41E-01	2.66E+05	5.63E-08
^{252}Cf	3.10E-03	1.82E-02	2.06E+06	1.51E-09	1.11E-01	3.38E+05	9.17E-09

* Derived from Table III.1 of Federal Guidance Report No. 12.[44]

† The effective dose equivalent coefficients provided are for ^{206}Rh.

‡ The activity given, and other coefficients and values, are for that of the alpha-emitting radioisotopes (e.g., ^{239}Pu or ^{241}Am). The dose from neutron-emitting radioisotopes was not considered.

Note: A P/C ratio of 0.1 or greater **(values in bold font)** indicate that that radioactive material likely poses a credible radiological threat in that scenario.

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44 Eckerman and Ryman, *External Exposure to Radionuclides in Air, Water, and Soil*, 57–73.

From Table 5, the typical activity in commercial practice would provide less than 0.001 (1/1,000) of the dose rate of 1.25 Sv/hr. from commercial devices that use ^{3}H (whole-body dose only), ^{32}P, ^{57}Co, ^{68}Ge, ^{85}Kr, ^{90}Sr (whole-body dose only), ^{99}Mo, ^{103}Pd, $^{106}Ru/Rh$, ^{109}Cd, ^{125}I, ^{131}I, ^{147}Pm, ^{153}Gd, ^{169}Yb, ^{170}Tm (whole-body dose only), ^{198}Au, ^{210}Po, ^{226}Ra, ^{238}Pu, $^{239}Pu/Be$, ^{241}Am, $^{241}Am/Be$, ^{244}Cm, or ^{252}Cf when dispersed within 30,000 m^3; therefore, these isotopes are also not credible candidates to be used in an aerosol RDD. From Table 5, the typical activity in commercial practice, when dispersed within 30,000 m^3, would provide more than 0.001 but less than 0.1 (1/10) of the dose rate of 1.25 Sv/hr. from commercial devices that use ^{75}Se, ^{137}Cs (whole-body dose only), ^{170}Tm (skin dose only), or ^{192}Ir; therefore, these isotopes are also unlikely to be credible candidates to be used in an aerosol RDD. Without regard to the physical form or to the engineering challenges associated with dispersing an aerosol of these isotopes, from the original 31 isotopes considered potentially dangerous by the IAEA, that leaves 3 isotopes—^{60}Co, ^{90}Sr (skin dose only), and ^{137}Cs (skin dose only)—as potentially credible candidates to be used in an aerosol RDD. This arrangement of the credibility of different radioisotopes as aerosol RDD threats for acute whole-body or cutaneous dose is illustrated in Figure 6 and Figure 7, respectively. Among these remaining isotopes of interest, ^{60}Co is of a form (metal) that would likely be difficult to produce as a fine powder; therefore, this isotope is unlikely to be a credible candidate to be used in an aerosol RDD. That leaves only ^{90}Sr and ^{137}Cs as credible candidates to be used in an aerosol RDD to produce a significant effective dose equivalent rate to the whole body or skin from submersion in a (semi-infinite cloud) of contaminated air, and they do so for the acute skin dose only.

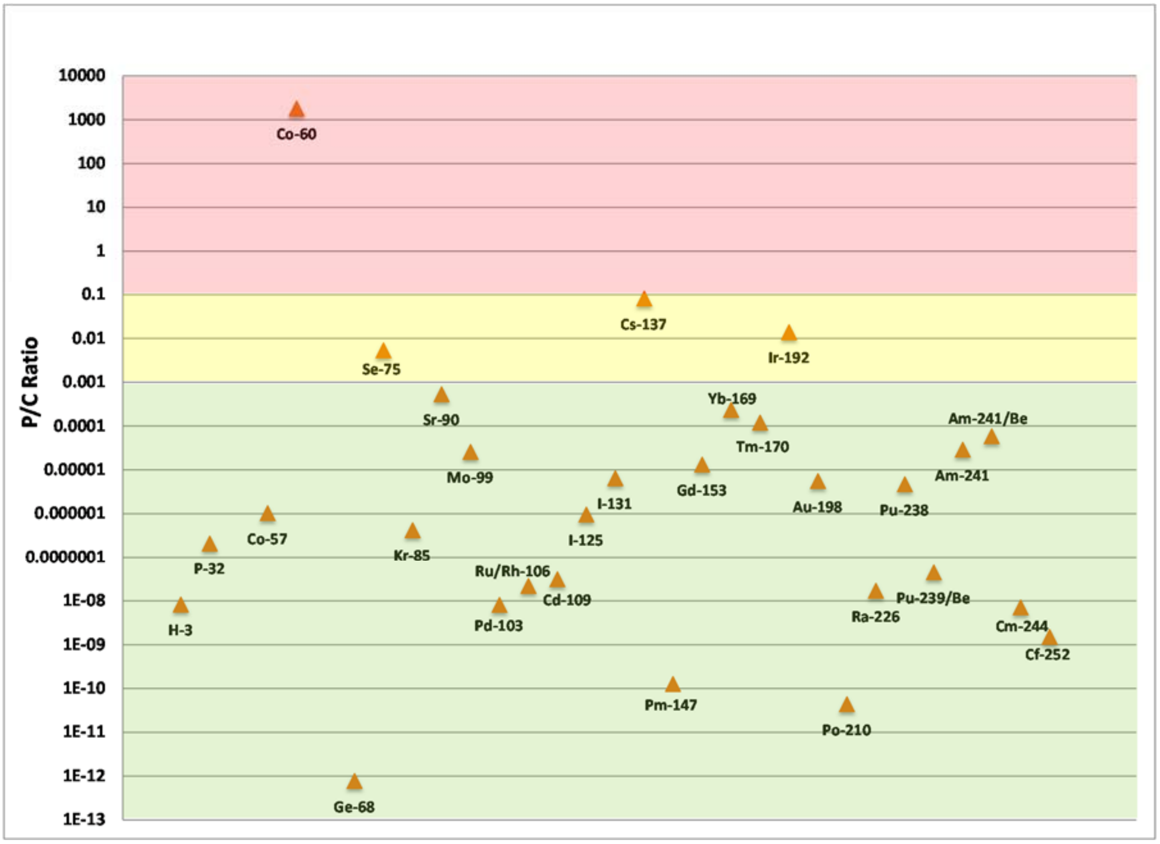

Figure 6. Aerosol RDD Radioisotope Selection Based Upon P/C Ratios for Dose from Submersion in Contaminated Air, Whole-Body Acute Effects

Note 1: There is no horizontal axis on this figure. The ordering of the isotopes by atomic mass units is a matter of convenience for the author and reader.

Note 2: Radioisotopes with P/C ratios less than 0.001 are highlighted in green, radioisotopes with P/C ratios greater than 0.001 but less than 0.1 (1/10) are highlighted in yellow, and the radioisotope with P/C ratios greater than 0.1 is highlighted in red.

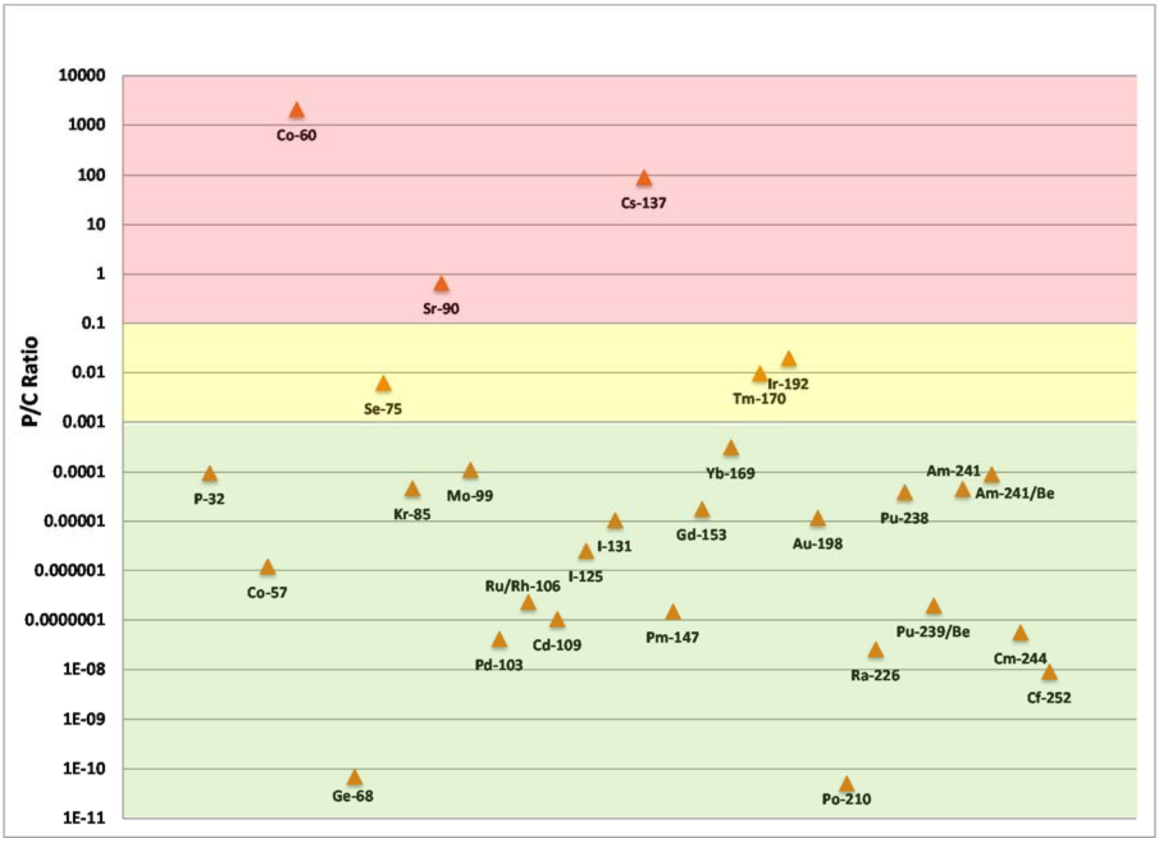

Figure 7. Aerosol RDD Radioisotope Selection Based Upon P/C Ratios for Dose from Submersion in Contaminated Air, Cutaneous Acute Effects

Note 1: There is no horizontal axis on this figure. The ordering of the isotopes by atomic mass units is a matter of convenience for the author and reader.

Note 2: Radioisotopes with P/C ratios less than 0.001 are highlighted in green, radioisotopes with P/C ratios greater than 0.001 but less than 0.1 (1/10) are highlighted in yellow, and radioisotopes with P/C ratios greater than 0.1 are highlighted in red.

Certain assumptions are made, based on the scenario of the five-story building with a volume of 30,000 m^3, to estimate whether a radioisotope should be considered a credible aerosol RDD threat based upon the committed RBE-weighted dose to the whole body or to the respiratory tract from inhalation of contaminated air:

- Building occupants are assumed to breathe contaminated air at a rate of 0.015 m^3/min. for 1 hr.[45])

[45] Standard breathing rates vary from 0.0075 m^3/min. for an individual at rest to 0.075 m^3/min. for an individual performing strenuous physical activity. A rate of 0.015 m^3/min. represents the breathing rate expected from light physical activity. See David W. Layton, “Metabolically Consistent Breathing Rates for Use in Dose Assessments,” *Health Physics* 64, no. 1 (January 1993): 30.

- The radioactive material in the contaminated air is assumed to be uniformly mixed within the entire contaminated volume and is assumed to be constant for the 1 hr. that building occupants breathe the air.
- The "inhalation intake fraction" is assumed to be 1×10^{-3} of the radioactive material present in the source (this inhalation intake fraction is the same as that used by the IAEA for the inhalation scenario[46]).

This scenario results in an estimate that building occupants inhale 0.90 m^3 of contaminated air. Table 6 provides the information useful for identifying the radioactive materials that would be a credible threat as an aerosol RDD, based upon dose from inhalation of contaminated air. The first two columns identify the radioisotopes being considered and what activities are typically used in practice ("P"). Two sensitive organs—the whole body and the respiratory tract— are considered. A separate evaluation is required for the whole-body dose and the lung dose from inhalation of the contaminated air. The third and sixth columns provide the dose conversion factors that convert activity inhaled (TBq) to dose equivalent rate (Sv/hr.) for the whole body (Column 3) and respiratory tract (Column 6). The fourth and seventh columns identify the "Activity of Concern (C)" that would be required to produce an effective dose equivalent rate of 1.25 Sv/hr. from an inhalation of 0.9 m^3 of air for isotopes uniformly mixed into a volume of 30,000 m^3 for the whole body (Column 4) and respiratory tract (Column 7). The fifth and eighth columns provide the associated P/C ratios.

The IAEA has published reference values that can be used to derive the estimate of the committed RBE-weighted dose to the whole body (red bone marrow) or respiratory tract (specifically, the alveolar-interstitial (AI) region of the respiratory tract) from inhalation (Sv/TBq).[47] The IAEA estimates the coefficient for the committed RBE-weighted dose to the whole body and respiratory tract from inhalation of air contaminated with ^{85}Kr to be zero (0.0)[48]; therefore, this isotope is not a viable candidate to be used in an aerosol RDD to cause a significant inhalation dose. From Table 6, the typical activity in commercial practice would provide less than 0.001 (1/1,000) of the dose of 1.25 Sv from commercial devices that use ^{3}H, ^{55}Fe, ^{57}Co, ^{63}Ni, ^{68}Ge, ^{99}Mo (whole body only), ^{103}Pd, ^{106}Ru/Rh, ^{109}Cd, ^{125}I, ^{131}I, ^{147}Pm, ^{153}Gd (whole body only), ^{169}Yb (whole body only), ^{198}Au, or ^{226}Ra (whole body only) after 1 hr. of breathing within a contaminated volume of 30,000 m^3; therefore, these isotopes are not credible candidates to be used in an aerosol RDD.

46 International Atomic Energy Agency. *Dangerous Quantities of Radioactive Materials (D-Values)*, 38.

47 Ibid., 83–93.

48 Ibid.

Table 6. Aerosol RDD Radioisotope Selection Based Upon Dose from Inhalation of Contaminated Air

		Whole Body			Respiratory Tract		
Radio-isotope Symbol	Activity in Practice (P) (Typical) (TBq)	Effective Dose Equivalent Coefficient (Sv/TBq)*	Activity of Concern (C) (TBq for 1.25 Gy from 0.9 m^3 over 30,000 m^3)	P/C Ratio	Effective Dose Equivalent Coefficient (Sv/TBq)*	Activity of Concern (C) (TBq for 1.25 Gy from 0.9 m^3 over 30,000 m^3)	P/C Ratio
^{3}H	2.60E-01	2.1E+01	2.0E+03	1.3E-04	2.1E+01	2.0E+03	1.3E-04
^{32}P	2.20E-02	2.6E+03	1.6E+01	1.4E-03	1.3E+04	3.2E+00	6.9E-03
^{55}Fe	7.40E-04	4.7E+01	8.9E+02	8.3E-07	2.0E+02	2.1E+02	3.6E-06
^{57}Co	1.90E-03	3.8E+01	1.1E+03	1.7E-06	1.2E+03	3.5E+01	5.5E-05
^{60}Co	1.50E+05	7.2E+02	5.8E+01	**2.6E+03**	9.3E+03	4.5E+00	**3.3E+04**
^{63}Ni	3.70E-04	4.4E+01	9.5E+02	3.9E-07	5.7E+02	7.3E+01	5.1E-06
$^{68}Ge^{+}$	1.10E-04	2.9E+02	1.4E+02	7.7E-07	2.6E+04	1.6E+00	6.9E-05
^{75}Se	3.00E+00	2.3E+02	1.8E+02	**1.7E-02**	1.4E+03	3.0E+01	**1.0E-01**
^{85}Kr	3.70E-02	0	N/A	N/A	0	N/A	N/A
$^{90}Sr^{+}$	7.40E+02	3.7E+03	1.1E+01	**6.6E+01**	4.5E+04	9.3E-01	**8.0E+02**
$^{99}Mo^{+}$	3.70E-02	2.0E+02	2.1E+02	1.8E-04	2.4E+03	1.7E+01	2.1E-03
$^{103}Pd^{+}$	1.10E-03	8.3E+00	5.0E+03	2.2E-07	1.2E+03	3.5E+01	3.2E-05
$^{106}Ru/Rh^{+}$	2.20E-05	2.6E+03	1.6E+01	1.4E-06	5.5E+04	7.6E-01	2.9E-05
^{109}Cd	1.10E-03	6.1E+01	6.8E+02	1.6E-06	3.7E+03	1.1E+01	9.8E-05
^{125}I	1.90E-02	1.5E+01	2.8E+03	6.8E-06	1.2E+01	3.5E+03	5.5E-06
^{131}I	3.70E-03	9.1E+01	4.6E+02	8.1E-06	8.8E+01	4.7E+02	7.8E-06
$^{137}Cs^{+}$	1.10E+05	7.9E+02	5.3E+01	**2.1E+03**	7.6E+02	5.5E+01	**2.0E+03**
^{147}Pm	1.90E-03	6.0E+01	6.9E+02	2.7E-06	2.4E+03	1.7E+01	1.1E-04
^{153}Gd	3.70E-02	4.3E+02	9.7E+01	3.8E-04	1.9E+03	2.2E+01	1.7E-03
^{169}Yb	1.90E-01	2.0E+02	2.1E+02	9.1E-04	4.5E+03	9.3E+00	**2.1E-02**
^{170}Tm	5.60E+00	4.4E+02	9.5E+01	**5.9E-02**	1.0E+04	4.2E+00	**1.3E+00**
^{192}Ir	3.70E+00	4.3E+02	9.7E+01	**3.8E-02**	9.4E+03	4.4E+00	**8.3E-01**
^{198}Au	3.00E-03	5.7E+01	7.3E+02	4.1E-06	2.0E+03	2.1E+01	1.4E-04
^{210}Po	1.10E-03	5.7E+04	7.3E-01	1.5E-03	1.2E+06	3.5E-02	**3.2E-02**
^{226}Ra	5.60E-04	2.2E+03	1.9E+01	3.0E-05	1.1E+06	3.8E-02	**1.5E-02**
^{238}Pu	1.00E+01	1.4E+04	3.0E+00	**3.4E+00**	1.6E+06	2.6E-02	**3.8E+02**
$^{239}Pu/Be^{\dagger}$	1.10E-01	1.3E+04	3.2E+00	**3.4E-02**	1.5E+06	2.8E-02	**4.0E+00**
^{241}Am	3.70E-01	7.4E+03	5.6E+00	**6.6E-02**	1.3E+06	3.2E-02	**1.2E+01**
$^{241}Am/Be^{\ddagger}$	7.40E-01	7.4E+03	5.6E+00	**1.3E-01**	1.3E+06	3.2E-02	**2.3E+01**
^{244}Cm	1.50E-02	7.8E+03	5.3E+00	2.8E-03	1.4E+06	3.0E-02	**5.0E-01**
^{252}Cf	3.10E-03	3.3E+04	1.3E+00	2.5E-03	2.5E+06	1.7E-02	**1.9E-01**

* Derived from Table 18 of the IAEA EPR-D Values.[49]

† The activity given and other coefficients and values are for that of the alpha-emitting radioisotopes (e.g., ^{239}Pu or ^{241}Am. The dose from neutron-emitting radioisotopes was not considered.

‡ Indicates the radioisotopes for which the progeny were significant sources of dose.

Note: A P/C ratio of 0.1 or greater **(values in bold font)** indicate that that radioactive material likely poses a credible radiological threat in that scenario.

[49] International Atomic Energy Agency. *Dangerous Quantities of Radioactive Materials (D-Values)*, 83–93.

From Table 6, the typical activity in commercial practice, when dispersed within 30,000 m^3, would provide more than 0.001 but less than 0.1 (1/10) of the dose of 1.25 Sv from commercial devices that use ^{32}P, ^{75}Se (for whole-body dose only), ^{99}Mo (for respiratory tract dose only), ^{153}Gd (respiratory tract dose only), ^{169}Yb (respiratory tract dose only), ^{192}Ir (whole-body dose only), ^{210}Po, ^{238}Pu (respiratory tract dose only), ^{239}Pu/Be (whole-body dose only), ^{226}Ra (respiratory tract only), ^{241}Am (whole-body dose only), ^{244}Cm (whole-body dose only), and ^{252}Cf (whole-body dose only) after 1 hr. of breathing; therefore, these isotopes are also unlikely to be credible candidates to be used in an aerosol RDD. Without regard to the physical form or to the engineering challenges associated with dispersing an aerosol of these isotopes, from the original 31 isotopes considered as potentially dangerous by the IAEA, that leaves 12 isotopes—^{60}Co, ^{75}Se (respiratory tract only), ^{90}Sr, ^{137}Cs, ^{170}Tm (respiratory tract only), ^{192}Ir (respiratory tract only), ^{238}Pu (whole body only), ^{239}Pu/Be (respiratory tract only), ^{241}Am (respiratory tract only), ^{241}Am/Be, ^{244}Cm (respiratory tract only), and ^{252}Cf (respiratory tract only)—as potentially credible candidates to be used in an aerosol RDD. This arrangement of the credibility of different radioisotopes as Aerosol RDD threats for acute whole-body or respiratory tract dose from inhalation is illustrated in Figure 8 and Figure 9, respectively. Among these remaining isotopes of interest, ^{60}Co (metal slugs or pellets), ^{75}Se (metal compound pellets), ^{170}Tm (metal), ^{192}Ir (metal), ^{239}Pu/Be (Intermetallic compound), and ^{244}Cm (solid) are of a form (metal) that would likely be difficult to produce as a fine powder; therefore, these isotopes are unlikely to be credible candidates to be used in an aerosol RDD. That leaves six isotopes—^{90}Sr, ^{137}Cs, ^{238}Pu, ^{241}Am, ^{241}Am/Be, and ^{252}Cf (respiratory tract only)—as credible candidates to be used in an aerosol RDD to produce a significant committed RBE-weighted dose to the whole body or respiratory tract from inhalation of contaminated air.

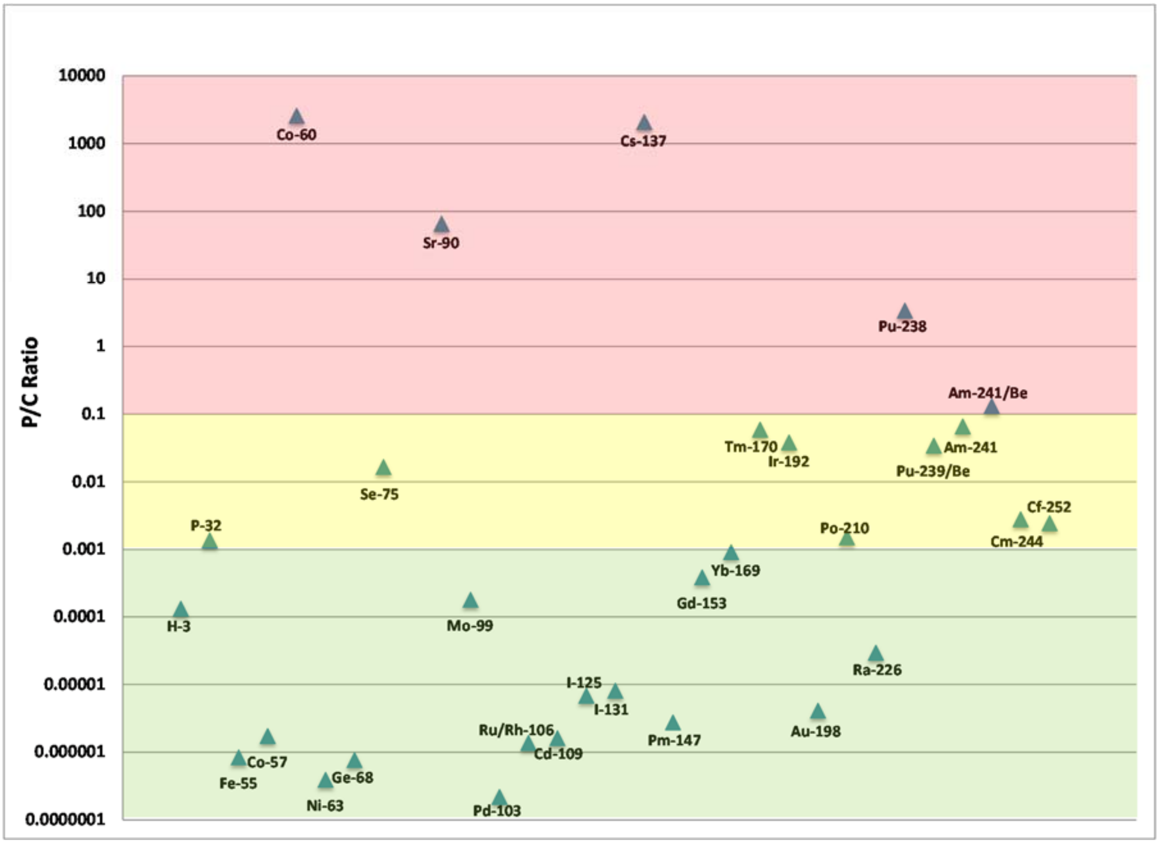

Figure 8. Aerosol RDD Radioisotope Selection Based Upon P/C Ratios for Dose from Inhalation of Contaminated Air, Whole-Body Acute Effects

Note 1: There is no horizontal axis on this figure. The ordering of the isotopes by atomic mass units is a matter of convenience for the author and reader.

Note 2: Radioisotopes with P/C ratios less than 0.001 are highlighted in green, radioisotopes with P/C ratios greater than 0.001 but less than 0.1 (1/10) are highlighted in yellow, and radioisotopes with P/C ratios greater than 0.1 are highlighted in red.

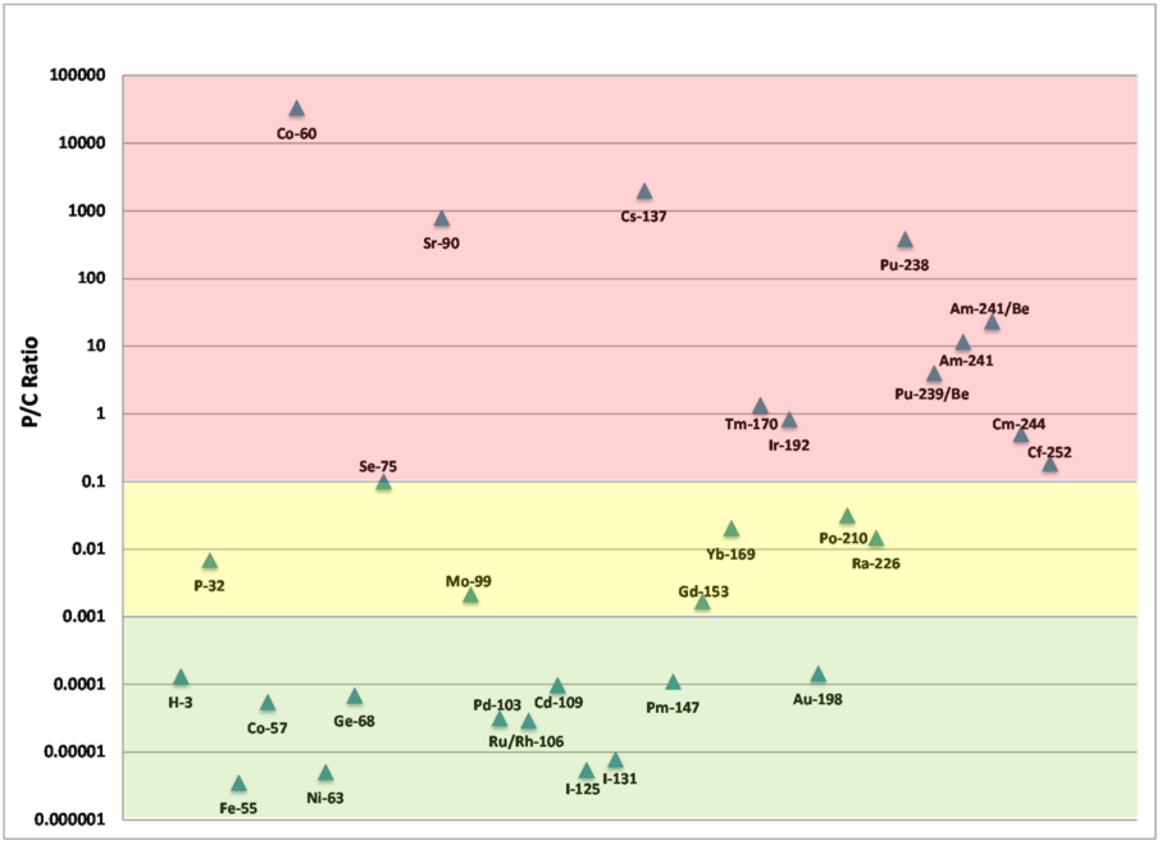

Figure 9. Aerosol RDD Radioisotope Selection Based Upon P/C Ratios for Dose from Inhalation of Contaminated Air, Respiratory Tract Acute Effects

Note 1: There is no horizontal axis on this figure. The ordering of the isotopes by atomic mass units is a matter of convenience for the author and reader.

Note 2: Radioisotopes with P/C ratios less than 0.001 are highlighted in green, radioisotopes with P/C ratios greater than 0.001 but less than 0.1 (1/10) are highlighted in yellow, and radioisotopes with P/C ratios greater than 0.1 are highlighted in red.

Certain assumptions are made, based on the scenario of the five-story building with a volume of 30,000 m^3 and each story as 3.3 m in height, to estimate whether a radioisotope should be considered as a credible aerosol RDD threat based upon the RBE-weighted dose rate conversion factor for contact exposure of the derma of the skin while in contaminated air:

- As a worst case, building occupants are assumed to have contamination on their skin equivalent to the total contamination in the air above the floor on each story of the building. Within a building, the airborne concentration (Bq/m^3) would be multiplied by the height of each story (3.3 m) to get the surface contamination level (Bq/m^2). For a five-story building with a volume of 30,000 m^3, the total surface area is approximately 9,100 m^2. The radioactive material is assumed to be uniformly distributed across this surface.
- The radioactive material is assumed to be in contact with the skin for 1 hr.

This scenario results in an estimate that building occupants are contaminated with radioactive material for 1 hr. Table 7 provides the information useful for identifying the radioactive materials that would be a credible threat as an aerosol RDD, based upon cutaneous dose from deposition of the radioisotope from contaminated air. The first two columns identify the radioisotopes being considered and what activities are typically used in practice ("P"). The sensitive organ considered is the skin. The third column provides the dose conversion factors that convert activity per unit area (TBq/m^2) on the skin to dose equivalent rate (Sv/hr.) for the skin. The fourth column identifies the "Activity of Concern (C)" that would be required to produce an effective dose equivalent rate of 1.25 Sv/hr. when uniformly deposited on a total area of 9,100 m^2. The fifth column provides the associated P/C ratios.

The IAEA has published reference values that can be used to derive the estimate of the RBE-weighted dose rate conversion factor for contact exposure of the derma of the skin ((Sv/hr.)/(TBq/m^2).[50] The IAEA estimates the coefficients for the RBE-weighted dose rate conversion factor for contact exposure of the derma of the skin with ^{3}H, ^{63}Ni, and ^{85}Kr to be zero (0.0)[51]; therefore, these isotopes are not viable candidates to be used in an aerosol RDD when considering skin contamination effects. From Table 7, the typical activity in commercial practice would provide less than 0.001 (1/1,000) of the dose of 1.25 Sv from commercial devices that use ^{32}P, ^{55}Fe, ^{57}Co, ^{68}Ge, ^{99}Mo, ^{103}Pd, $^{106}Ru/Rh$, ^{109}Cd, ^{125}I, ^{131}I, ^{147}Pm, ^{153}Gd, ^{169}Yb, ^{198}Au, ^{210}Po, ^{226}Ra, ^{238}Pu, $^{239}Pu/Be$, ^{241}Am, $^{241}Am/Be$, ^{244}Cm or ^{252}Cf after 1 hr. of contact exposure of the derma of the skin across a contaminated surface of 9,100 m^2; therefore, these isotopes are also not credible candidates to be used in an aerosol RDD when considering skin contamination effects. From Table 7, the typical activity in commercial practice would provide less than 0.1 (1/10) but more than 0.001 of the dose of 1.25 Sv from commercial devices that use ^{75}Se, ^{170}Tm, and ^{192}Ir after 1 hr. of contact exposure of the derma of the skin across a contaminated surface of 9,100 m^2; therefore, these isotopes are also unlikely to be credible candidates to be used in an aerosol RDD when considering skin contamination effects.

[50] Ibid,. 94-102.

[51] Ibid.

Table 7. Aerosol RDD Radioisotope Selection
Based Upon Cutaneous Dose from Contaminated Deposited on the Skin

		Skin Contamination		
Radioisotope Symbol	**Activity in Practice (P) (Typical) (TBq)**	**Effective Dose Equivalent Coefficient (Sv/hr.)/(TBq/m²)***	**Activity of Concern (C) (TBq for 1.25 Sv/hr. over 9,100 m²)**	**P/C Ratio**
^{3}H	2.6E-01	0	N/A	N/A
^{32}P	2.2E-02	1.3E+02	8.8E+01	2.5E-04
^{55}Fe	7.4E-04	1.5E+00	7.7E+03	9.6E-08
^{57}Co	1.9E-03	4.0E+00	2.9E+03	6.6E-07
^{60}Co	1.5E+05	1.2E+01	9.3E+02	**1.6E+02**
^{63}Ni	3.7E-04	0	N/A	N/A
^{68}Ge	1.1E-04	1.4E+02	7.9E+01	1.4E-06
^{75}Se	3.0E+00	4.7E+00	2.4E+03	1.2E-03
^{85}Kr	3.7E-02	0	N/A	N/A
^{90}Sr	7.4E+02	1.8E+02	6.3E+01	**1.2E+01**
^{99}Mo	3.7E-02	8.3E+01	1.4E+02	2.7E-04
^{103}Pd	1.1E-03	9.4E-01	1.2E+04	9.1E-08
^{106}Ru/Rh	2.2E-05	1.6E+02	7.0E+01	3.1E-07
^{109}Cd	1.1E-03	1.3E+00	8.8E+03	1.3E-07
^{125}I	1.9E-02	1.5E+00	7.3E+03	2.6E-06
^{131}I	3.7E-03	4.0E+01	2.9E+02	1.3E-05
^{137}Cs	1.1E+05	5.0E+01	2.3E+02	**4.9E+02**
^{147}Pm	1.9E-03	7.6E-02	1.5E+05	1.3E-08
^{153}Gd	3.7E-02	1.8E+00	6.3E+03	5.9E-06
^{169}Yb	1.9E-01	4.3E+00	2.6E+03	7.2E-05
^{170}Tm	5.6E+00	7.6E+01	1.5E+02	**3.7E-02**
^{192}Ir	3.7E+00	4.7E+01	2.4E+02	**1.5E-02**
^{198}Au	3.0E-03	7.6E+01	1.5E+02	2.0E-05
^{210}Po	1.1E-03	3.3E-05	3.4E+08	3.2E-12
^{226}Ra	5.6E-04	1.8E+02	6.4E+01	8.7E-06
^{238}Pu	1.0E+01	2.2E-01	5.3E+04	1.9E-04
^{239}Pu/Be†	1.1E-01	8.3E-02	1.4E+05	8.0E-07
^{241}Am	3.7E-01	1.3E+00	8.5E+03	4.3E-05
^{241}Am/Be†	7.4E-01	1.3E+00	8.5E+03	8.7E-05
^{244}Cm	1.5E-02	1.8E-01	6.2E+04	2.4E-07
^{252}Cf	3.1E-03	1.3E+02	8.5E+01	3.6E-05

* Derived from Table 19 of the IAEA EPR-D Values.[52]

† The activity given and other coefficients and values are for that of the alpha-emitting radioisotopes (e.g., ^{239}Pu or ^{241}Am). The dose from neutron-emitting radioisotopes was not considered.

Note: A P/C ratio of 0.1 or greater (values in bold font) indicate that that radioactive material likely poses a credible radiological threat in that scenario.

[52] International Atomic Energy Agency. *Dangerous Quantities of Radioactive Materials (D-Values)*, 94–102.

Without regard to the physical form or to the engineering challenges associated with dispersing an aerosol of these isotopes or evenly distributing them on a surface, from the original 31 isotopes considered as potentially dangerous by the IAEA, that leaves 3 isotopes—^{60}Co, ^{90}Sr, and ^{137}Cs—as potentially credible candidates to be used in an aerosol RDD. This arrangement of the credibility of different radioisotopes as aerosol RDD threats for acute cutaneous dose from deposition is illustrated in Figure 10. Among these remaining isotopes of interest, ^{60}Co is of a form (metal) that would likely be difficult to produce as a fine powder; therefore, this isotope is unlikely to be a credible candidate to be used in an aerosol RDD. That leaves only two isotopes—^{90}Sr and ^{137}Cs—as credible candidates to be used in an aerosol RDD to produce a significant committed RBE-weighted dose rate when considering skin contamination effects.

The technological requirements, coupled with low impacts, take away from the credibility of an attack consisting of an aerosolized dispersal of radioactive material. "…, creating and disseminating an aerosol or a vapour quickly and surreptitiously is difficult, and fatalities resulting from an inhalation attack would probably be measured in tens, …."[53] Similar effects can be achieved at a lower risk through chemical agents as evidenced by the Sarin attack on the Tokyo metro perpetrated by Aum Shinrikyo. This attack left 19 dead and injured nearly 5,000 exposed individuals.[54] Therefore, an aerosol RDD is not a credible threat for producing significant casualties in this scenario.

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[53] James M. Acton, M. Brooke Rogers, and Peter D. Zimmerman, "Beyond the Dirty Bomb: Re-thinking Radiological Terror," *Survival: Global Politics and Strategy* 49, no. 3 (2007): 156, doi:10.1080/00396330701564760.

[54] Dr. Yasuo Seto, "The Sarin Gas Attack in Japan and the Related Forensic Investigation" (The Hague, The Netherlands: Organisation for the Prohibition of Chemical Weapons, June 1, 2001), https://www.opcw.org/news/article/the-sarin-gas-attack-in-japan-and-the-related-forensic-investigation/.

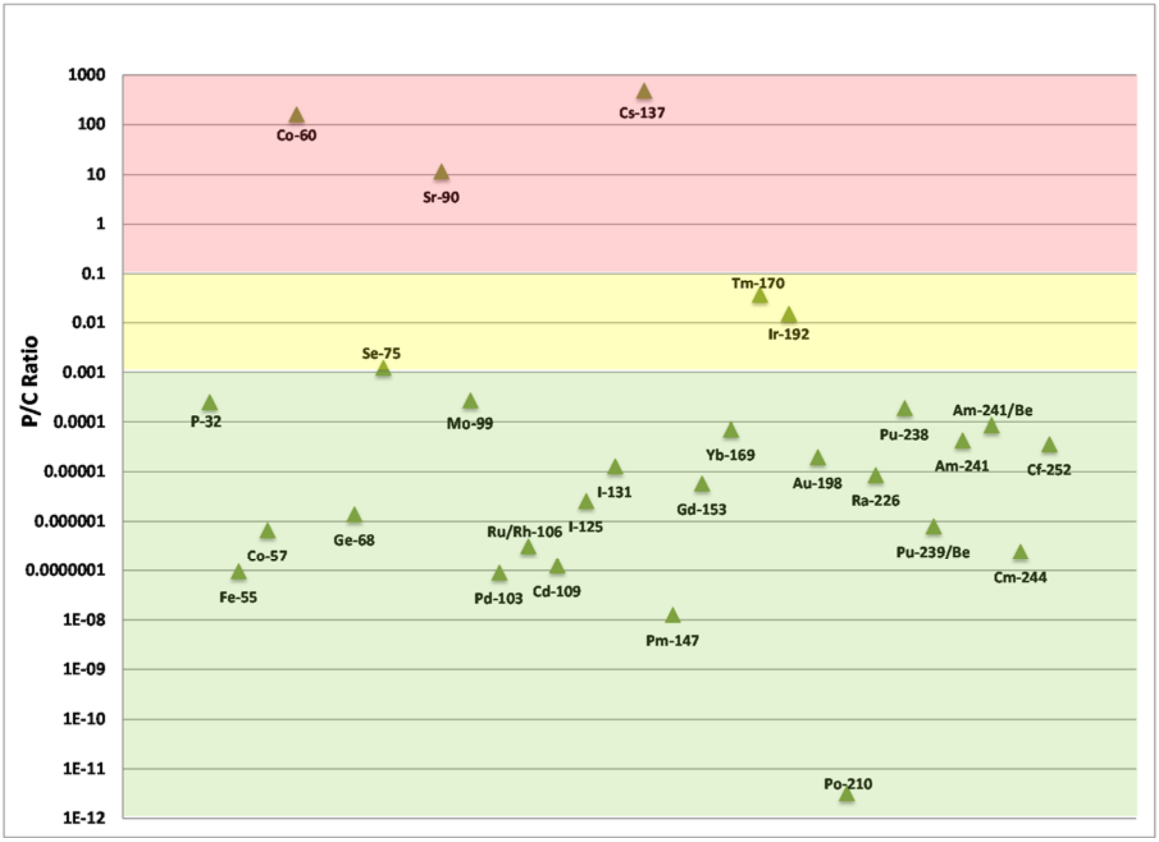

Figure 10. Aerosol RDD Radioisotope Selection Based Upon P/C Ratios for Cutaneous Dose from Contaminated Deposited on the Skin

Note 1: There is no horizontal axis on this figure. The ordering of the isotopes by atomic mass units is a matter of convenience for the author and reader.

Note 2: Radioisotopes with P/C ratios less than 0.001 are highlighted in green, radioisotopes with P/C ratios greater than 0.001 but less than 0.1 (1/10) are highlighted in yellow, and radioisotopes with P/C ratios greater than 0.1 are highlighted in red.

4. Ingestion RDD

Ingestion of radioactive material allows the radiation to be emitted in intimate contact with living tissue, potentially resulting in damage even from alpha and beta particles. Radioisotopes that emit high LET radiation, such as alpha or beta emitters, are effective for the ingestion delivery vector since they have the potential to cause more radiation damage than gamma emitters when internal to the body. Calculations of absorbed dose carry a QF (multiplier) of 20 for alpha-emitting particles, making smaller amounts of material harmful. Therefore, contaminating food and water sources could pose a significant threat. Worth noting is the targeted use of ^{210}Po against Russian Spy Alexander Litvinenko in

2006. In the first documented case of an effective radiological attack, Litvinenko unknowingly ingested the substance and succumbed to ARS a few days later.[55]

The desired impact of an ingestion delivery vector is immediate health effects and widespread panic over the contamination of the food or water supply. However, given the control and monitoring of food/water sources in the United States, it is extremely difficult to contaminate ingested materials. Even if a malicious actor were to bypass these controls successfully, he would require an exorbitant amount of radioactive material to produce widespread radiation effects due to dispersal among a high volume of foodstuffs. Further complicated by the limitations on availability of alpha-emitting radioisotopes in industry, significant obstacles have to be overcome in the acquisition of radioactive material. These obstacles reinforce the prevailing belief among subject matter experts (SMEs) that the ingestion delivery vector is better suited for targeted attacks against one or a small group of people (e.g., the Litvinenko affair). In addition, other poisons, such as arsenic and cyanide, can achieve similar results without the need for a source of ^{210}Po, which is only produced in government-controlled nuclear reactors.

The IAEA has published reference values that can be used to derive the estimate of the committed RBE-weighted dose to the whole body (red bone marrow) from ingestion (Sv/TBq).[56] Ingestion RDDs require large amounts of radioactive material to be dispersed within a large volume; therefore, the quantity of radioactive material and the security (availability) of sources are important contributing factors to radioisotope selection.

An example of a plausible ingestion RDD scenario, similar to that for the aerosol RDD, is the dispersal of a 260-TBq source of ^{137}Cs (amount in a typical blood or tissue irradiator) into a volume of 40,000 L (40 m^3 or 5,280 gal., approximately the volume of a large tanker truck). Assuming that the ^{137}Cs is uniformly distributed over the volume (6.5 TBq/m^3), this distribution would result in a committed RBE-weighted dose to the whole body (red bone marrow) from ingestion of 2 L per day for 5 days of about 150 Sv. This example uses an IAEA Category 1 source, which should be difficult to acquire. Category 1 and 2 sources are more secure but have the potential to disperse contamination within a larger volume or at a higher concentration level if used in an ingestion RDD.

Certain assumptions, similar to those for the scenario for the aerosol RDD and based upon the committed RBE-weighted dose to the whole body from ingestion of contaminated

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[55] Mary Jordan and Peter Finn, "Radioactive Poison Killed Ex-Spy," *The Washington Post Foreign Service*, November 25, 2006, http://www.washingtonpost.com/wp-dyn/content/article/2006/11/24/AR2006112400410.html.

[56] International Atomic Energy Agency. *Dangerous Quantities of Radioactive Materials (D-Values)*, 94-101.

water, are made to estimate whether a radioisotope should be considered as a credible ingestion RDD threat:

- The radioactive material is 100% water-soluble.
- The radioisotope is uniformly dissolved into a volume of 40,000 L of water (40 m^3, or 5,280 gal., approximately the volume of a large tanker truck).
- An exposed individual drinks 2 L of contaminated water per day for a period of 5 days, for a total of 10 L.[57]

Table 8 provides the information useful for identifying the radioactive materials that would be a credible threat as an ingestion RDD, based upon whole-body dose from ingestion of the radioisotope from contaminated food or water. The first two columns identify the radioisotopes being considered and what activities are typically used in practice ("P"). The sensitive organ considered is the red bone marrow, which is assumed to be equivalent to the whole-body dose. The third column provides the dose conversion factors that convert the ingested activity (TBq) on the skin to the committed RBE-weighted dose to the whole body (red bone marrow) from ingestion (Sv). The fourth column identifies the "Activity of Concern (C)" that would be required to produce a committed RBE-weighted dose of 1.25 Sv when from drinking 10 L from 40 m^3 of contaminated water. The fifth column provides the associated P/C ratios.

The IAEA estimates the coefficient for the committed RBE-weighted dose to the whole body (red bone marrow) from ingestion of water contaminated with ^{85}Kr to be zero (0.0)[58]; therefore, this isotope is not a viable candidate to be used in an ingestion RDD to cause a significant committed dose. From Table 8, the typical activity in commercial practice would provide less than 0.001 (1/1,000) of the dose of 1.25 Sv from commercial devices that use ^{32}P, ^{55}Fe, ^{57}Co, ^{63}Ni, ^{68}Ge, ^{103}Pd, ^{106}Ru/Rh, ^{109}Cd, ^{125}I, ^{131}I, ^{147}Pm, ^{153}Gd, ^{198}Au, ^{226}Ra, ^{244}Cm, ^{252}Cf or ^{241}Am/Be after drinking 10 L of a contaminated volume of 40 m^3; therefore, these isotopes are also not credible candidates to be used in an ingestion RDD. From Table 8, the typical activity in commercial practice would provide less than 0.1 (1/10) but more than 0.001 of the dose of 1.25 Sv from commercial devices that use ^{3}H, ^{99}Mo, ^{169}Yb, ^{170}Tm, ^{210}Po, ^{239}Pu/Be or ^{241}Am, after drinking 10 L of a contaminated volume of 40 m^3; therefore, these isotopes are also unlikely to be credible candidates to be used in an ingestion RDD. Without regard to the physical form or engineering challenges associated with dispersing or dissolving these isotopes, from the original 31 isotopes considered as potentially dangerous by the IAEA, that leaves 6 isotopes—^{60}Co, ^{75}Se, ^{90}Sr, ^{137}Cs, ^{192}Ir, and ^{238}Pu—as potentially credible candidates to be used in an ingestion RDD.

[57] Ibid., 39.

[58] Ibid.

Table 8. RDD Radioisotope Selection Based Upon Dose from Ingestion of Contaminated Water

Radioisotope Symbol	Activity in Practice (P) (Typical) (TBq)	Effective Dose Equivalent Coefficient (Sv/TBq)*	Activity of Concern (C) (TBq for 1.25 Sv from Drinking 10 L from 40 m^3 L)	P/C Ratio
^{3}H	2.6E-01	2.1E+01	2.4E+02	1.1E-03
^{32}P	2.2E-02	6.4E+03	7.8E-01	**2.8E-02**
^{55}Fe	7.4E-04	1.8E+01	2.8E+02	2.7E-06
^{57}Co	1.9E-03	3.5E+01	1.4E+02	1.3E-05
^{60}Co	1.5E+05	5.8E+02	8.6E+00	**1.7E+04**
^{63}Ni	3.7E-04	1.6E+00	3.1E+03	1.2E-07
^{68}Ge‡	1.1E-04	2.9E+02	1.7E+01	6.4E-06
^{75}Se	3.0E+00	5.8E+02	8.6E+00	**3.5E-01**
^{85}Kr	3.7E-02	0	N/A	N/A
^{90}Sr‡	7.4E+02	4.0E+03	1.3E+00	**5.9E+02**
^{99}Mo‡	3.7E-02	6.1E+02	8.2E+00	4.5E-03
^{103}Pd‡	1.1E-03	1.5E+00	3.3E+03	3.3E-07
^{106}Ru/Rh‡	2.2E-05	2.9E+02	1.7E+01	1.3E-06
^{109}Cd	1.1E-03	1.5E+01	3.3E+02	3.3E-06
^{125}I	1.9E-02	1.3E+01	3.8E+02	4.9E-05
^{131}I	3.7E-03	9.6E+01	5.2E+01	7.1E-05
^{137}Cs‡	1.1E+05	2.3E+03	2.2E+00	**5.1E+04**
^{147}Pm	1.9E-03	9.4E-01	5.3E+03	3.6E-07
^{153}Gd	3.7E-02	2.5E+01	2.0E+02	1.9E-04
^{169}Yb	1.9E-01	7.0E+01	7.1E+01	2.7E-03
^{170}Tm	5.6E+00	8.1E+00	6.2E+02	9.1E-03
^{192}Ir	3.7E+00	1.9E+02	2.6E+01	**1.4E-01**
^{198}Au	3.0E-03	7.6E+01	6.6E+01	4.6E-05
^{210}Po	1.1E-03	2.3E+04	2.2E-01	5.1E-03
^{226}Ra	5.6E-04	7.7E+03	6.5E-01	8.6E-04
^{238}Pu	1.0E+01	2.1E+02	2.4E+01	**4.2E-01**
^{239}Pu/Be†	1.1E-01	2.0E+02	2.5E+01	4.4E-03
^{241}Am	3.7E-01	1.2E+02	4.2E+01	8.9E-03
^{241}Am/Be†	7.4E-01	1.2E+02	4.2E+01	**1.8E-02**
^{244}Cm	1.5E-02	1.2E+02	4.2E+01	3.6E-04
^{252}Cf	3.1E-03	6.4E+02	7.8E+00	4.0E-04

* Derived from Table 19 of the IAEA EPR-D Values.[59]

† The activity given, and other coefficients and values, are for that of the alpha-emitting radioisotope (e.g., ^{239}Pu or ^{241}Am). The dose from neutron-emitting radioisotope was not considered.

‡ Indicates the radioisotopes for which the progeny were significant sources of dose.

Note: A P/C ratio of 0.1 or greater **(values in bold font)** indicate that that radioactive material likely poses a credible radiological threat in that scenario.

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[59] Ibid., 94–101.

This arrangement of the credibility of different radioisotopes as ingestion RDD threats for acute whole-body dose is illustrated in Figure 11. Among these remaining isotopes of interest, ^{60}Co (metal slugs or pellets), ^{75}Se (metal compound, pellets), ^{90}Sr (metal oxide ceramic), ^{192}Ir (metal), and ^{238}Pu (metal oxide ceramic) are of a form (metal) that would be unlikely to be water soluble; therefore, these isotopes are also unlikely to be credible candidates to be used in an ingestion RDD. That leaves one isotope—^{137}Cs—as a credible candidate to be used in an ingestion RDD to produce a significant committed RBE-weighted dose to the whole body from ingestion of contaminated water.

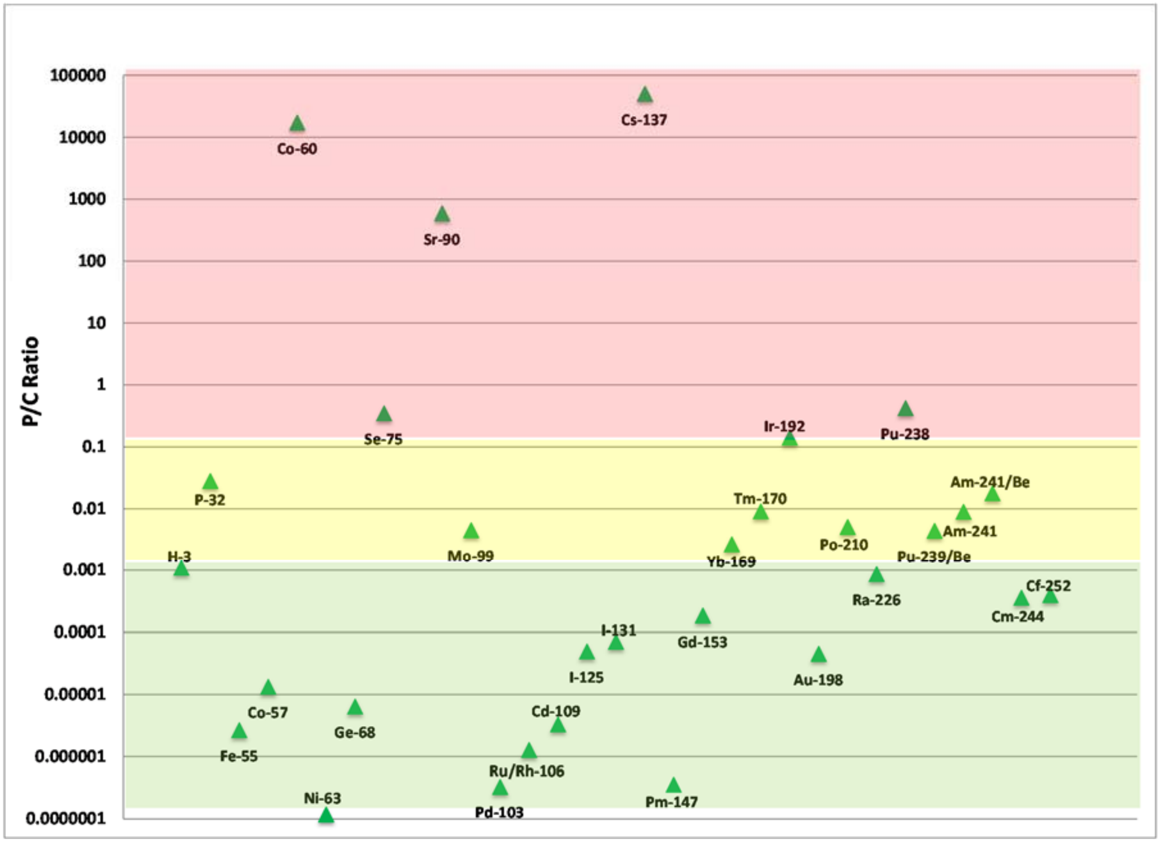

Figure 11. RDD Radioisotope Selection Based Upon P/C Ratios for Dose from Ingestion of Contaminated Water

Note 1: There is no horizontal axis on this figure. The ordering of the isotopes by atomic mass units is a matter of convenience for the author and reader.

Note 2: Radioisotopes with P/C ratios less than 0.001 are highlighted in green, radioisotopes with P/C ratios greater than 0.001 but less than 0.1 (1/10) are highlighted in yellow, and radioisotopes with P/C ratios greater than 0.1 are highlighted in red.

Despite the high impacts of ingested radioactive sources, the obstacles against the ingestion delivery vector are too numerous; therefore, ingestion-based RDDs do not qualify as a credible threat against a majority of the populace.

5. Immersion RDD

Immersion in gaseous radioactive material is the most difficult of the scenarios considered in this paper. Only a limited number of radioactive materials are gasses at room temperature and pressure (e.g., Tritium or various isotopes of argon, krypton, or xenon). This gaseous radioactive material is different from the aerosolized radioactive material described in Table 5, Table 6, and Table 7. It would require a high quantity of radioactive material in a relatively small enclosed space to result in significant dose to the whole body (red marrow); therefore, immersion in radioactive material is not considered a credible threat.

4. Conclusions

This analysis sought to identify and illustrate the credibility of using radioactive materials for REDs or RDDs.

A multitude of radiological material dispersion mechanisms are possible. Each RDD method of dispersal is tailored to produce a different impact. The main proposed use of radiological weapons is to induce fear in a population, and these weapons are sometimes termed “weapons of mass disruption” due to the relatively low number of casualties they cause in contrast to the disproportionate fear surrounding a radiological attack. The fear is based upon the invisible nature of radiation and plays upon public ignorance of its effects. Malicious actors can harness this fear by employing RDDs to deny area access, cause psychological casualties, and/or cause acute radiation injury.

Common industrial devices that use radioisotopes include gauges, food irradiators, radiographic cameras, well logging devices, thickness measurement tools, brachytherapy devices, medical tracers, and RTGs. This list is by no means complete; rather, it gives a general idea of the wide variety of sources that use radioisotopes. Each radioactive source contains differing amounts, forms, and protective shielding of radioisotopes. Evaluating a number of different RDD scenarios, ^{60}Co, ^{75}Se, ^{90}Sr, ^{137}Cs, ^{170}Tm, ^{192}Ir, ^{238}Pu, ^{239}Pu/Be, ^{241}Am, ^{241}Am/Be, ^{244}Cm, and ^{252}Cf were evaluated as credible candidates to be used in some form—often several forms—of radiological weapon threat.

This analysis leads to the conclusion that radiological weapons should be considered as credible threats to U.S. military operations. Although there are technological challenges, radioactive material is available commercially in amounts that provide a credible capability to develop a radiological weapon. Further analysis could seek to clarify assumptions made and expand the scope of this project.

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Appendix A.
Radiation Basics

Radiation is excess energy emitted in the form of particles and rays. Unstable nuclei spontaneously undergo this process to reach a more stable state. Through a process known as radioactive decay, radioisotopes lose their radioactivity and become stable atoms.[1] The common measure of radioactive decay is half-life, the time required for the matter to exhibit half of its activity. Radiation can be categorized as either non-ionizing or ionizing radiation. Radiation that does not have enough energy to displace electrons is referred to as "non-ionizing radiation." Examples of this kind of radiation are sound waves, visible light, and microwaves.[2] Ionizing radiation has the energy to move electrons and is defined as "particulate (alpha, beta, and neutron) and electromagnetic (X-ray and gamma) radiation of sufficient energy to displace electrons from atoms, producing ions."[3] Ionizing radiation can cause biological harm to humans by radiation-induced chemical changes within cells and by damage to the genetic material (deoxyribonucleic acid (DNA)) of the cell, resulting in mutations.

Individual radioisotopes undergo radioactive decay through four primary modes: alpha, beta, gamma, and/or neutron emission. Alpha (α) particles are of the same structure as a Helium-4 nucleus. The particle is not penetrating but damaging if inhaled or ingested. Beta (β) radiation consists of emitting negatively charged particles (electrons) that are moderately penetrating. Because beta particles are much smaller and have less charge than alpha particles, they generally travel further into tissues than alpha particles. (An electron emitted from the electron shell of an atom will have the same properties as a beta particle.) As a result, the cellular damage from beta particle radiation is more dispersed is tissue.[4] Beta particles constitute a cutaneous threat, along with the more traditional ingestion and

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1 United States Nuclear Regulatory Commission. "Radiation Basics." Last updated October 17, 2014. http://www.nrc.gov/about-nrc/radiation/health-effects/radiation-basics.html.

2 U.S. Environmental Protection Agency, "Radiation Basics: Electromagnetic Spectrum," last updated May 4, 2016, https://www.epa.gov/radiation/radiation-basics#tab-1.

3 Joint Chiefs of Staff, *Operations in Chemical, Biological, Radiological, and Nuclear Environments*, Joint Publication 3-11 (Washington, DC: Department of the Army, Department of the Navy, Department of the Air Force, United States Marine Corps, 04 October 2013), http://www.dtic.mil/doctrine/new_pubs/jp3_11.pdf.

4 U.S. Environmental Protection Agency, "Radiation Basics: Types of Ionizing Radiation," last updated May 4, 2016, https://www.epa.gov/radiation/radiation-basics#tab-2.

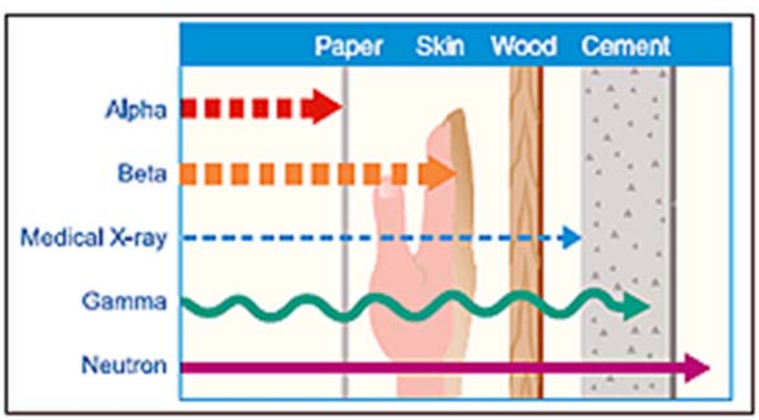
inhalation routes of exposure. Gamma (γ) radiation is an energetic photon that is very penetrating and often accompanies other radiation. It is given off when an atom falls to a less excited state (excess energy expended). (X-rays emitted during the transition of an electron from one energy level to another will have the same properties as gamma radiation.) Neutrons (n) are electrically neutral particles with the mass of one atomic mass unit (1.66×10^{-27} g). Neutrons interact by collision (transfer of kinetic energy) with nuclei and, thus, are generally more likely to cause changes in materials with more closely spaced nuclei. Such materials include water and tissue. The radiological characteristics of the different types of radiation are summarized in Table A-1.

Table A-1. Radiation Decay Modes Table

Radiation	Symbol	Components	Penetration	Hazard
Alpha	α	Charged particle, similar to a helium nucleus	Low	Internal
Beta	β	Negatively charged particle, similar to an electron	Medium	Internal and cutaneous
Gamma	γ	High-energy wave consisting of a charged photon	High	External and internal
Neutron	n	High-energy nuclear particle	High	External with the added ability to make objects radioactive

Source: Adapted from United States Nuclear Regulatory Commission, "Radiation Basics," last updated October 17, 2014, http://www.nrc.gov/about-nrc/radiation/health-effects/radiation-basics.html.

"Penetration" describes the threat posed by each type of ionizing radiation. Various materials are required to shield the different types of radiation and can range from a simple layer of clothing to lead shielding. A visual summary depicting penetration rates of ionizing radiation is depicted in Figure A-1.



Source: United States Nuclear Regulatory Commission, "Radiation Basics," last updated October 17, 2014, http://www.nrc.gov/about-nrc/radiation/health-effects/radiation-basics.html.

Figure A-1. Penetration of Ionizing Radiation Figure

The impact of ionizing radiation on the human body varies with dose, dose rate, type of radiation, shielding, tissues exposed, and several other factors. Dose is a term used to express how much radiation energy is deposited in material. The basic unit of dose is the gray, which is equal to a joule per kilogram (1 Gy = 1 J/kg). The effectiveness of a dose to produce radiation damage in tissue is expressed by the quantity "dose equivalent." The basic unit of dose equivalent is the sievert (Sv) and is calculated by multiplying the dose by a quality factor (Sv = Gy × QF) (see Table A-2). Thus, the energy deposited by radiation can subsequently be expressed in terms of the absorbed dose (Gy), or dose equivalent (Sv), based on the amount of energy absorbed and what form or radiation is considered. These terms provide a basis for the analysis of health implications as a result of radiation exposure. Detailed definitions for these terms are provided in Appendix D.

Table A-2. Radiation Quality Factors Table

Type of Radiation	Symbol	Quality Factor
Alpha	α	20
Beta	β	1
Gamma	γ	1
Neutron	n	10

Source: Adapted from United States Nuclear Regulatory Commission, "§ 20.1004 Units of Radiation Dose," last updated December 2, 2015, http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/part020-1004.html.

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Appendix B.
Some Isotopes and Practices of Interest

Table B-1 shows some isotopes and practices of interest

Table B-1. Isotopes and Practices of Interest

Isotope	Practice	Activity in Practice (P) (TBq) Minimum	Maximum	Typical
H-3	Tritium targets	1.10E-01	1.10E+00	2.60E-01
	Electron capture detectors	1.90E-03	1.10E-02	9.30E-03
	Lightning preventers	7.40E-03	7.40E-03	7.40E-03
P-32	Medical unsealed	2.20E-03	2.20E-02	2.20E-02
Fe-55	X-ray fluorescence analyzers	1.10E-04	5.00E-03	7.40E-04
Co-57	Mossbauer spectrometry	1.90E-04	3.70E-03	1.90E-03
	X-ray fluorescence analyzers	5.60E-04	1.50E-03	9.30E-04
Co-60	Irradiators: sterilization and food preservation	1.90E+02	5.60E+05	1.50E+05
	Irradiators: self-shielded	5.60E+01	1.90E+03	9.30E+02
	Multi-beam teletherapy (gamma knife)	1.50E+02	3.70E+02	2.60E+02
	Teletherapy	3.70E+01	5.60E+02	1.50E+02
	Irradiators: blood/tissue	5.60E+01	1.10E+02	8.90E+01
	Industrial radiography	4.10E-01	7.40E+00	2.20E+00
	Calibration facilities	2.00E-02	1.20E+00	7.40E-01
	Brachytherapy: high/medium dose rate	1.90E-01	7.40E-01	3.70E-01
	Level gauges	3.70E-03	3.70E-01	1.90E-01
	Blast furnace gauges	3.70E-02	7.40E-02	3.70E-02
	Dredger gauges	9.30E-03	9.60E-02	2.80E-02
Ni-63	Electron capture detectors	1.90E-04	7.40E-04	3.70E-04
Ge-68	Positron emission tomography (PET) scans	3.70E-05	3.70E-04	1.10E-04
Se-75	Industrial radiography	3.00E+00	3.00E+00	3.00E+00
Kr-85	Thickness gauges	1.90E-03	3.70E-02	3.70E-02
Sr-90	Radioisotopic thermoelectric generators (RTGs)	3.30E+02	2.50E+04	7.40E+02
	Calibration facilities	7.40E-02	7.40E-02	7.40E-02
	Thickness gauges	3.70E-04	7.40E-03	3.70E-03
	Brachytherapy: low dose-rate eye plaques and permanent implants	7.40E-04	1.50E-03	9.30E-04
Mo-99	Diagnostic isotope generators	0.037	0.37	0.037

Table B-1. Isotopes and Practices of Interest (Continued)

Isotope	Practice	Activity in Practice (P) (TBq) Minimum	Maximum	Typical
Pd-103	Brachytherapy: low dose-rate eye plaques and permanent implants	1.10E-03	1.10E-03	1.10E-03
Ru/Rh-106	Brachytherapy: low dose-rate eye plaques and permanent implants	8.10E-06	2.20E-05	2.20E-05
Cd-109	X-ray fluorescence analyzers	1.10E-03	5.60E-03	1.10E-03
	Bone densitometry	0.00074	0.00074	0.00074
I-125	Bone densitometry	0.0015	0.03	0.019
	Brachytherapy: low dose rate	1.50E-03	1.50E-03	1.50E-03
I-131	Medical unsealed	0.0037	0.0074	0.0037
Cs-137	Irradiators: sterilization and food preservation	1.90E+02	1.90E+05	1.10E+05
	Irradiators: self-shielded	9.30E+01	1.60E+03	5.60E+02
	Irradiators: blood/tissue	3.70E+01	4.40E+02	2.60E+02
	Teletherapy	1.90E+01	5.60E+01	1.90E+01
	Calibration facilities	5.60E-02	1.10E+02	2.20E+00
	Level gauges	3.70E-02	1.90E-01	1.90E-01
	Conveyor gauges	3.70E-03	1.50E+00	1.10E-01
	Brachytherapy: high/medium dose rate	1.10E-01	3.00E-01	1.10E-01
	Dredger gauges	7.40E-03	3.70E-01	7.40E-02
	Spinning pipe gauges	7.40E-02	1.90E-01	7.40E-02
	Well logging	3.70E-02	7.40E-02	7.40E-02
	Brachytherapy: low dose rate	3.70E-04	2.60E-02	1.90E-02
	Fill-level, thickness gauges	1.90E-03	2.40E-03	2.20E-03
	Moisture/density gauges	0.0003	0.00041	0.00037
	Density gauges	0.0003	0.00037	0.00037
Pm-147	Thickness gauges	1.90E-03	1.90E-03	1.90E-03
Gd-153	Bone densitometry	0.00074	0.056	0.037
Yb-169	Industrial radiography	9.30E-02	3.70E-01	1.90E-01
Tm-170	Industrial radiography	7.40E-01	7.40E+00	5.60E+00
Ir-192	Industrial radiography	1.90E-01	7.40E+00	3.70E+00
	Brachytherapy: high/medium dose rate	1.10E-01	4.40E-01	2.20E-01
	Brachytherapy: low dose rate	7.40E-04	2.80E-02	1.90E-02
Au-198	Brachytherapy: low dose rate	3.00E-03	3.00E-03	3.00E-03
Po-210	Static eliminators	0.0011	0.0041	0.0011
Ra-226	Brachytherapy: low dose rate	1.90E-04	1.90E-03	5.60E-04
	Moisture/density gauges	0.000074	0.00015	0.000074
	Lightning preventers	2.60E-07	3.00E-06	1.10E-06
Pu-238	RTGs	1.00E+00	1.00E+01	1.00E+01
	Pacemakers	1.10E-01	3.00E-01	1.10E-01
Pu-239/Be	Calibration sources	7.40E-02	3.70E-01	1.10E-01

Table B-1. Isotopes and Practices of Interest (Continued)

Isotope	Practice	Activity in Practice (P) (TBq)		
		Minimum	Maximum	Typical
Am-241	Calibration facilities	1.90E-01	7.40E-01	3.70E-01
	Thickness gauges	1.10E-02	2.20E-02	2.20E-02
	Bone densitometry	0.001	0.01	0.005
	Fill-level, thickness gauges	4.40E-04	4.40E-03	2.20E-03
	Static eliminators	0.0011	0.0041	0.0011
	Lightning preventers	4.80E-05	4.80E-04	4.80E-05
Am-241/Be	Well logging	1.90E-02	8.50E-01	7.40E-01
	Research reactor startup sources	7.40E-02	1.90E-01	7.40E-02
	Moisture detectors	1.90E-03	3.70E-03	1.90E-03
	Moisture/density gauges	0.00037	0.0037	0.0019
Cm-244	Thickness gauges	7.40E-03	3.70E-02	1.50E-02
Cf-252	Brachytherapy: low dose rate	3.10E-03	3.10E-03	3.10E-03
	Conveyor gauges	1.40E-03	1.40E-03	1.40E-03
	Well logging	1.00E-03	4.10E-03	1.10E-03
	Moisture/density gauges	1.1E-06	2.6E-06	2.2E-06

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Appendix C.
Isotope Characteristics

Table C-1 provides characteristics of the 31 different isotopes of interest.

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Table C-1. Isotope Characteristics

Isotope	Half-Life	Specific Activity (TBq/g)	Radiation Type	Maximum Energy (MeV)	D2-Value (TBq)	QoC (g)	Application	Primary Form	Threat Assessment
H-3	12.32 y	359	β (100%)	0.018564	2000	5.571030641	Luminescent dials/ detectors/nuclear reaction byproduct	Liquid (tritiated water)	Extremely low levels of radiation when diluted in water (less than comparable naturally occurring background radiation)
C-14	5730 y	0.165	β	0.156	50	303.030303	Tracer	Solid	Low specific activity means that it would not create sufficient radiation for the purpose of weapons use
Na-24	15.00 h	322000	β	0.171	20	6.21118E-05	Tracer	Salt/powder/metal	Half-life is too short for the isotope to be weaponized before it decays. In addition, it would not provide area denial function
P-32	14.3 d	10600	β		20	0.001886792	Tracer	Powder	Not normally available to end users in significant quantities
Cl-36	308000 y	0.00122	β	0.714	20	16393.44262	Measure age of water	Powder	Too low of activity means that it would not create sufficient radiation for the purpose of weapons use
Mn-54	312 d	287	γ (100%)	0.835	40	0.139372822		Metal	
Fe-55	270 y	89.1	X-ray	0.006	800	8.978675645	Detectors	Metal	X-ray does not provide the harmful radiation required for weapons. Can be shielded against by clothing
Co-60	527 y	41.8	β and γ (99.98%)	1.3225	30	0.717703349	Irradiators/ brachytherapy/ calibration facilities/ level gauges	Metal	Strong gamma emitter with wide application
Ni-63	96 y	2.19	β	0.0659	60	27.39726027	Detectors/light sensors	Metal	Low energy emissions (65 KeV). Expensive to produce via current methods of neutron irradiation of Ni-62 in a reactor

Table C-1. Isotope Characteristics (Continued)

Isotope	Half-Life	Specific Activity (TBq/g)	Radiation Type	Maximum Energy (MeV)	D2-Value (TBq)	QoC (g)	Application	Primary Form	Threat Assessment
Zn-65	244 d	305	ε (51%) and β+ (1.5%)	1.115 and 0330	300	0.983606557	Used to predict the behavior of heavy metal components in effluents from mining waste water	Metal	ε does not provide harmful radiation required for weapons
Ga-67	3.26 d	22100	ε leading to γ (35.7%)	0.093	400	0.018099548			Half-life is too short for the isotope to be weaponized before it decays. In addition, it would not provide area denial function
Se-75	120 d	537	ε leading to γ (59.8%)	0.265	200	0.372439479	Industrial radiography/ brachytherapy	Metal	Quickly becoming a replacement for Ir-192 as an industry standard only increases its availability
Sr-82	25.00 d	2360	ε leading to γ (9%)	3.18 and 0.777	5	0.002118644		Metal	ε does not provide harmful radiation required for weapons
Kr-85	10.72 y	14.5	β and γ		2000	137.9310345	Thickness gauges/spent fuel rods	Gas	Radioactive gas would pose a significant inhalation hazard. However, it is difficult to find in significant amounts
Sr-90	29.1 y	5.05	β		1	0.198019802	Radioisotopic thermoelectric generators (RTGs); industrial gauging	Ceramic	Available in large quantities (notably, large unsecured sources such as Russian RTGs)
Mo-99	2.75 d	17700	β	1.214	20	0.00112994	Diagnostic isotope generators	Metal	Half-life is too short for the isotope to be weaponized before it decays. In addition, it would not provide area denial function
Tc-99m	6.02 h	194000	γ		700	0.003608247	Tracer	Metal	Half-life is too short for the isotope to be weaponized before it decays. In addition, it would not provide area denial function

Table C-1. Isotope Characteristics (Continued)

Isotope	Half-Life	Specific Activity (TBq/g)	Radiation Type	Maximum Energy (MeV)	D2-Value (TBq)	QoC (g)	Application	Primary Form	Threat Assessment
I-123	13.2 h	71400	ε leading to γ (83.4%)	0.159	30	0.000420168	Medical application (thyroid disorders)	Solid/salt	Half-life is too short for the isotope to be weaponized before it decays. In addition, it would not provide area denial function
I-125	60.1 d	643	ε		0.4	0.000622084	Brachytherapy	Solid/salt	ε does not provide harmful radiation required for weapons
I-129	15700000 y	0.00000653	γ		N/A	N/A	Used to check some radioactivity counters in *in vitro* diagnostic testing laboratories	Solid/salt	Too low of activity means that it would not create sufficient radiation for the purpose of weapons use
I-131	8.04 d	4590	β and γ		0.2	43573E-05	Nuclear fusion product/medical	Solid/salt	
Cs-137	30.17 y	3.22	β (0.011%) and γ (99.9856%)	0.512 and 0.662	20	6.211180124	Irradiators/teletherapy/level gauges/calibration facilities	Salt (CsCl)	Combination of desired attributes and commercial availability make it a candidate for a radiological weapon. Low cost
Pm-147	262 y	34.4	β		40	1.162790698	Thickness gauges/RTG fuel (narrowly applied)/illuminators	Metal	Not normally available to end users in significant quantities
Gd-153	242 d	130	ε leading to γ (64.7%)	0.042	80	0.615384615	Bone densitometry	Solid	Not normally available to end users in large quantities
Yb-169	32.0 d	893	ε		30	0.033594625	Industrial radiography	Metal	ε does not provide harmful radiation required for weapons
Tm-170	129 d	220	β		20	0.090909091	Industrial radiography	Metal	Prohibitively expensive to obtain
W-188	69.4 d	370	β		8	0.021621622		Sodium tungstate solution	
Ir-92	74.0 d	340	β and γ		20	0.058823529	Industrial radiography/brachytherapy	Metal	Combination of desired attributes and commercial availability make it a candidate for a radiological weapon.

Table C-1. Isotope Characteristics (Continued)

Isotope	Half-Life	Specific Activity (TBq/g)	Radiation Type	Maximum Energy (MeV)	D2-Value (TBq)	QoC (g)	Application	Primary Form	Threat Assessment
Au-198	2.69 d	9070	β		30	0.003307607	Tracer	Metal	Not normally available to end users in large quantities
Ti-204	3.78 y	17.2	β and ε		20	1.162790698	Limited manufacturing use	Solid	Not normally available to end users in large quantities
Pb-210	22.20 y	2.83	β	0.061	0.3	0.106007067		Metal	Naturally occurring and readily available
Po-210	1600 y	0.0366	α	5.35	0.06	0.000359281	Static eliminators	Metal foil	Only commercially available to end users in small quantities. The concern is in limited situations with aggregate or bulk quantities
Ra-226	1600 y	0.0366	α	4.782	0.07	1.912568306	Moisture/density gauges/lightning rods	Salt	Combination of desired attributes and commercial availability make it a candidate for a radiological weapon
PU-238	87.7 y	0.634	α		0.08	0.94637224		Solid/pressed ceramic	Combination of desired attributes and commercial availability make it a candidate for a radiological weapon
Am-241	432.2 y	0.127	α (85%) and γ (36%)	5.49 and 0.059	0.06	0.472440945	Calibration facilities	Pressed ceramic powder	Combination of desired attributes and commercial availability make it a candidate for a radiological weapon
Cm-243	28.5 y	1.91	α		0.02	0.104712042		Solid	Not normally available to end users in large quantities
Cm-244	18.1 y	3	α		0.05	0.016666667		Solid	Not normally available to end users in large quantities
Am-241/Be	432 y		n				Research reactor startup sources/well logging/material analysis/thickness gauges	Compressed powder	Difficult to obtain, but exposure to neutron emission makes it a possible candidate for a radiation exposure device (RED)

Table C-1. Isotope Characteristics (Continued)

Isotope	Half-Life	Specific Activity (TBq/g)	Radiation Type	Maximum Energy (MeV)	D2-Value (TBq)	QoC (g)	Application	Primary Form	Threat Assessment
Pu-239/Be			n				Calibration sources		Difficult to obtain, but exposure to neutron emission makes it a possible candidate for an RED
Cf-252	2.64 y	19.9	n		0.1	0.005025126	Well logging	Solid	Difficult to obtain, but exposure to neutron emission makes it a possible candidate for an RED

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Appendix D.
Definitions

Note: *The information in this section was taken directly from the websites of the following organizations: Health Physics Society (HPS), Nuclear Regulatory Commission (NRC), Centers for Disease Control and Prevention (CDC), International Atomic Energy Association (IAEA), and so forth. None of the definitions represent original work by the author of this study.*

Absorbed dose: Absorbed dose is used for purposes of radiation protection and assessing dose or risk to humans in general terms. Absorbed dose is the amount of radiation absorbed in an organ or tissue (i.e., the amount of radiation energy that has been left in cells, tissues, or organs). Absorbed dose is usually defined as energy deposited (joule) per unit of mass (kilogram). See gray and rad.

Acute Radiation Syndrome (ARS): ARS is a serious illness that can happen when a person is exposed to very high levels of radiation, usually over a short period of time.

Becquerel: Becquerel (Bq) is the unit in the International System of Units (SI—Système international d'unités) to replace the curie (see curie). It is based upon the radioactive decay rate of the radioisotope. One Bq is equal to one disintegration per second (dps).

Curie: Curie (Ci) is the traditional unit used to describe the amount of radioactive material present or strength of the source. See Becquerel.

Deterministic Effect: A deterministic effect is a health effect of radiation for which generally a threshold level of dose exists above which the severity of the effect is greater for a higher dose. Such an effect is described as a "severe deterministic effect" if it is fatal or life threatening or results in a permanent injury that decreases the quality of life.

Dose: Dose is a general term used to express how much radiation energy is deposited in something (a person or other material). The energy deposited can subsequently be expressed in terms of the absorbed, equivalent, committed, and/or effective dose based on the amount of energy absorbed and in what tissues.

Effective dose: Radiation exposures to the human body, whether from external or internal sources, can involve all or a portion of the body. The health effects of one unit of dose to the entire body are more harmful than the same dose to only a portion of the body. To enable radiation protection specialists to express partial-body exposures (and the accompanying doses) to portions of the body in terms of an equal dose to the whole body, the concept of effective dose was developed. Effective dose, then, is the dose to the whole body that would carry with it the same risk as a higher dose to only a portion of the body. As an example, based on this idea, 80 millisievert to the lungs is roughly the same potential detriment as 10 millisievert to the whole body.

Equivalent dose: Equivalent dose is a dose quantity used for radiation protection purposes that takes into account the chance that a type of radiation will cause an effect. Different types of radiation (alpha, beta, and gamma) interact with human tissues differently. Some types of radiation leaving a lot of energy in the tissue, and others leaving very little energy in the tissue. The energy that is left is what partially determines whether an effect will occur. Therefore, different types of radiation are assigned numbers based on how effective that type of radiation is at leaving its energy in the tissue, thus having more potential to cause an effect. By using equivalent dose, we are provided an indication of the potential for biological effects. From this equivalent dose, risk comparisons can be made between different types of radiation.

Exposure: Exposure is commonly used in reference to being around a radiation source (e.g., if a person has a chest x-ray, he/she is exposed to radiation). By definition, exposure is a measure of the amount of ionizations produced in air by photon radiation.

Gray: Gray (Gy) is the unit in the SI used to describe absorbed radiation dose. It describes a specific amount of energy absorbed in a medium (e.g., human tissue). In the traditional units, the rad describes absorbed radiation dose. One gray is equal to 100 rad.

Radiation: Radiation is energy given off by matter in the form of rays or high-speed particles … [Forces within an atom] work toward a strong, stable balance by getting rid of excess atomic energy (radioactivity). In that process, unstable nuclei may emit a quantity of energy, and this spontaneous emission is what we call radiation.

Roentgen (R): Roentgen (R) is used to describe radiation exposure. This term describes the amount of ionization in air. In the SI, the coulomb per kilogram ($C\ kg^{-1}$) describes radiation exposure. One roentgen is equal to $2.58 \times 10^{-4}\ C\ kg^{-1}$.

Sievert: Sievert (Sv) is the unit in SI to describe equivalent or effective radiation dose. One sievert is equal to 100 rem.[1] It is a unit that is the product of energy absorbed in human tissues and the quality of the radiation being absorbed (the ability of the radiation to cause damage).

[1] Rem is the term used to describe equivalent or effective radiation dose.

Appendix E.
Illustrations

Figures

Tables

Appendix F.
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Appendix G.
Abbreviations

ADT	androgen deprivation therapy
AI	alveolar-interstitial
ALARA	as low as reasonably achievable
ARS	Acute Radiation Syndrome
Bq	becquerel
C	Activity of Concern
CDC	Centers for Disease Control and Prevention
Ci	curie
CsCl	cesium chloride
DNA	deoxyribonucleic acid
dps	disintegration per second
EPA	Environmental Protection Agency
EPR	Emergency Preparedness and Response
FSU	Former Soviet Union
GAO	Government Accountability Office
Gy	gray
Gy-Eq	Gray-Equivalent
Gy-Eq	gray-equivalent
HPS	Health Physics Society
IAEA	International Atomic Energy Agency
IDA	Institute for Defense Analyses
IED	improvised explosive device
IND	improvised nuclear device
ITDB	Incident and Trafficking Database
LANL	Los Alamos National Laboratory
LET	linear energy transfer
mSv	millisievert
NATO	North Atlantic Treaty Organization
NRC	Nuclear Regulatory Commission
OTSG	Office of the Surgeon General
P	Activity of Practice
PET	positron emission tomography
R	roentgen
RBE	Relative Biological Effectiveness
RDD	radiation dispersal device
RED	radiation exposure device
RTG	radioisotope thermoelectric generator

SI	Système international d'unités (International System of Units)
SME	subject matter expert
Sv	sievert
TBq	terabecquerel
TECDOC	Technical Document
U.S.	United States
UR	Unlimited Release (LANL Publication)
USSR	Union of Soviet Socialist Republics

Isotopes

Americium-241	^{241}Am
Americium-241/Beryllium	$^{241}Am/Be$
Cadmium-109	^{109}Cd
Caesium-137	^{137}Cs
Californium-252	^{252}Cf
Cobalt-57	^{57}Co
Cobalt-60	^{60}Co
Curium-244	^{244}Cm
Gadolinium-153	^{153}Gd
Germanium-68	^{68}Ge
Gold-198	^{198}Au
Hydrogen-3 (Tritium)	^{3}H
Iodine-125	^{125}I
Iodine-131	^{131}I
Iridium-192	^{192}Ir
Iron-55	^{55}Fe
Krypton-85	^{85}Kr
Molybdenum-99	^{99}Mo
Nickel-63	^{63}Ni
Palladium-103	^{103}Pd
Phosphorus-32	^{32}P
Plutonium-238	^{238}Pu
Plutonium-239/Beryllium	$^{239}Pu/Be$
Polonium-210	^{210}Po
Promethium-147	^{147}Pm
Radium-226	^{226}Ra
Ruthenium-106/Rhodium	$^{106}Ru/Rh$
Selenium-75	^{75}Se
Strontium-90	^{90}Sr
Thulium-170	^{170}Tm
Ytterbium-169	^{169}Yb

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14. ABSTRACT
A simple methodology for evaluating the credibility of radiological material as a threat was developed. This methodology compares the largest quantity of radioactive material typically found in a single instrument or device that is available in commercial practice ("P") with the quantity of radioactive material necessary for it to pose a sufficient threat to be of concern ("C"). If the ratio of "P" to "C" is high (0.1 or greater), it is more credible that the radioactive material could be used in a radiological weapon. The P/C ratio is constructed so that the higher the P/C ratio the more credible it is that a suitable source can be found to pose the threat of concern. The conclusion is that radiological weapons should be considered as credible threats to US military operations. Evaluating a number of different RDD scenarios, ^{60}Co, ^{75}Se, ^{90}Sr, ^{137}Cs, ^{170}Tm, ^{192}Ir, ^{238}Pu, ^{239}Pu/Be, ^{241}Am, ^{241}Am/Be, ^{244}Cm, and ^{252}Cf were evaluated as credible candidates to be used in some form, often several forms, of radiological weapon threat. Radioactive material is available commercially in amounts that provide a credible capability to pose a threat as a radiological weapon.

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